CRANFIELD UNIVERSITY

CHRIS SWINERD

ON THE DESIGN OF HYBRID SIMULATION MODELS, FOCUSSING ON THE AGENT-BASED SYSTEM DYNAMICS COMBINATION

CRANFIELD DEFENCE AND SECURITY

CENTRE FOR SIMULATION AND ANALYTICS

PhD THESIS

Academic year: 2014

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ABSTRACT

There is a growing body of literature reporting the application of hybrid simulations to inform decision making. However, guidance for the design of such models, where the output depends upon more than one modelling paradigm, is limited. The benefits of realising this guidance include facilitating efficiencies in the general modelling process and reduction in project risk (both across measures of time, cost and quality). Focussing on the least well researched modelling combination of agent-based simulation with system dynamics, a combination potentially suited to modelling complex adaptive systems, the research contribution presented here looks to address this shortfall.

Within a modelling process, conceptual modelling is linked to model specification via the design transition. Using standards for systems engineering to formally define this transition, a critical review of the published literature reveals that it is frequently documented. However, coverage is inconsistent and consequently it is difficult to draw general conclusions and establish best practice. Therefore, methods for extracting this information, whilst covering a diverse range of application domains, are investigated.

A general framework is proposed to consistently represent the content of conceptual models; characterising the key elements of the content and interfaces between them. Integrating this content in an architectural design, design classes are then defined. Building on this analysis, a decision process is introduced that can be used to determine the utility of these design classes. This research is benchmarked against reported design studies considering system dynamics and discrete-event simulation and demonstrated in a case study where each design archetype is implemented. Finally, the potential for future research to extend this guidance to other modelling combinations is discussed.

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Chapter 1 INTRODUCTION

1.1 Aim

Hybrid simulation models are defined here as computer models whose output depends on a contribution from more than one simulation modelling paradigm. Chahal, Eldabi and Young (2013) have recently confirmed that there is no guidance for the design and utility of hybrid simulation models despite the growing body of literature describing a diverse range of its applications. They partly address this shortfall by developing methodological design guidance for the modelling combination of system dynamics (SD) with discrete-event simulation (DES) when applied to the healthcare domain. Without limiting the scope to a particular application or domain, the aim of this thesis is to develop methodological design guidance for the modelling combination of agent-based simulation (ABS) with system dynamics; referred to here as hybrid AB-SD modelling. This combination is less well researched and understood than others, such as the SD-DES combination, and it offers a potentially useful approach to the modelling of complex adaptive systems (Macal and Hummel, n.d.; Macal and North, 2006). Many of the challenging problems confronting analysts and operational researchers today are related to such systems. As presented in Table 1-1, the publication rate associated with this modelling combination is presently outstripping that associated with any other combination of these simulation modelling paradigms, making research in this area timely.

The preliminary literature reviews conducted for this research to determine to what extent the design of hybrid AB-SD models has been reported concurs with that usefully reported by Lättilä, Hilletofth and Lin (2010). In essence, as detailed in Chapter 2, the literature describes the influence of ABS on SD design, the philosophical correspondence between ABS and SD paradigms, or it describes the application of hybrid AB-SD models to specific problems.

Lättilä, Hilletofth and Lin (2010) conclude that more hybrid AB-SD models should be implemented. As well as reporting simulation results, they suggest that lessons identified during the 'simulation process' (described later as the general modelling process) should also be reported as this would be valuable to modellers and would improve the quality of models and associated modelling techniques.

Such guidance is important because it informs the selection and application of appropriate modelling techniques and, by inference, enhances support to decision making: virtually all models, be they physical, mathematical, analytic or simulation, are used to support decision making in one form or another. The adoption and application of such guidance will improve simulation projects in a number of ways such as through time and cost efficiencies (i.e. using appropriate models), facilitating the verification and validation process (fundamental to the quality assurance of simulation models) and in design audit (essential for the credibility of a model). This thesis is, therefore, relevant to decision makers (who have a vested interest in support based on appropriate models), to practitioners and academics of modelling and simulation (who seek to refine tools and techniques), and to students (who will gain from an appreciation of underlying design choices for multi-method or hybrid approaches to simulation modelling).

1.1.1 Research Interest in Computer Simulation Modelling

The three simulation modelling paradigms of SD (Forrester, 1961), ABS (Holland, 1998 and earlier scientific publications) and DES (Tocher, 1963) are well established with much openly published literature. In Table 1-1, the number of publications listed per decade in the Scopus® database (Elsevier B.V., 2013) is presented for combinations of these paradigms where they are cited in the title only or in the title, abstract or keywords. Examples of the search strings used are:

Search for SD only in title or title, abstract and keyword - TITLE("system dynamics") AND TITLE(model) for title only or TITLE-ABS-KEY("system dynamics") AND TITLE-ABS-KEY(model).

Search for SD, ABS and DES in title only - TITLE("system dynamics") AND TITLE("agent-based") AND TITLE("discrete event") AND TITLE(model).

Whilst not a comprehensive survey, the results of this search provide an indication of the relative levels of research interest over time; any research specifically considering design guidance or multi-method approaches would form a subset of these findings. SD and DES have the longest pedigree, although SD appears to have been more active than DES during the 1970s. Although ABS was introduced most recently, its scientific contribution has risen rapidly and presently outnumbers the others in terms of publication rate. When considering multiple paradigms, the combination of SD and DES has the longest track record, although that of SD and ABS is presently making a comparable contribution; indeed, it had overtaken the SD-DES combination in the wider search category at the time the comparison was made.

Table 1-1: Number of publications citing combinations of modelling paradigms in title only (top) or title, abstract or keyword (bottom); Scopus® (Elsevier B.V., 2013)

Decade	Title only						
	SD	DES	ABS	SD & DES	SD & ABS	DES & ABS	SD & DES & ABS
2010-pres.	198	101	619	3	3	1	0
2000-2009	228	195	733	3	4	1	0
1990-1999	39	79	17	0	0	0	0
1980-1989	39	29	0	1	0	0	0
1970-1979	20	2	0	0	0	0	0
1960-1969	0	0	1	0	0	0	0
Decade	Title, Abstract or Keyword						
	SD	DES	ABS	SD & DES	SD & ABS	DES & ABS	SD & DES & ABS
2010-pres.	3420	2169	4021	53	103	59	12
2000-2009	5056	4572	5869	93	66	84	3
1990-1999	1852	1833	245	20	1	1	0
1980-1989	649	463	24	2	0	0	0
1970-1979	213	78	6	2	0	0	0
1960-1969	7	5	1	0	0	0	0

The total numbers of publications that consider multiple paradigms are presently at least an order of magnitude below that which report on a single paradigm. Given the historical profile for publication rates of single paradigms, this deficit may indicate the growth potential for hybrid modelling over the next decade.

1.2 Methodology

Figure 1-1 provides an overview of the research conducted and how this is either represented or reflected in this thesis which comprises seven chapters and four annexes. This research has essentially followed two paths: an inductive research path using the literature to both identify the research gap and to source information with which to address that gap, and a modelling path. As presented in Figure 1-1, this thesis primarily reports the inductive research path, but incorporates lessons learnt from the modelling that has otherwise been reported separately (Swinerd, 2012; Swinerd and McNaught, 2012b; Swinerd and McNaught, 2014; Swinerd and McNaught, n.d.). The dark-grey boxes in Figure 1-1 identify the research objectives and the light-grey boxes the scope of subsequent research. The stars indicate where research contributions have been made along the way and which are presented in Chapter 7.

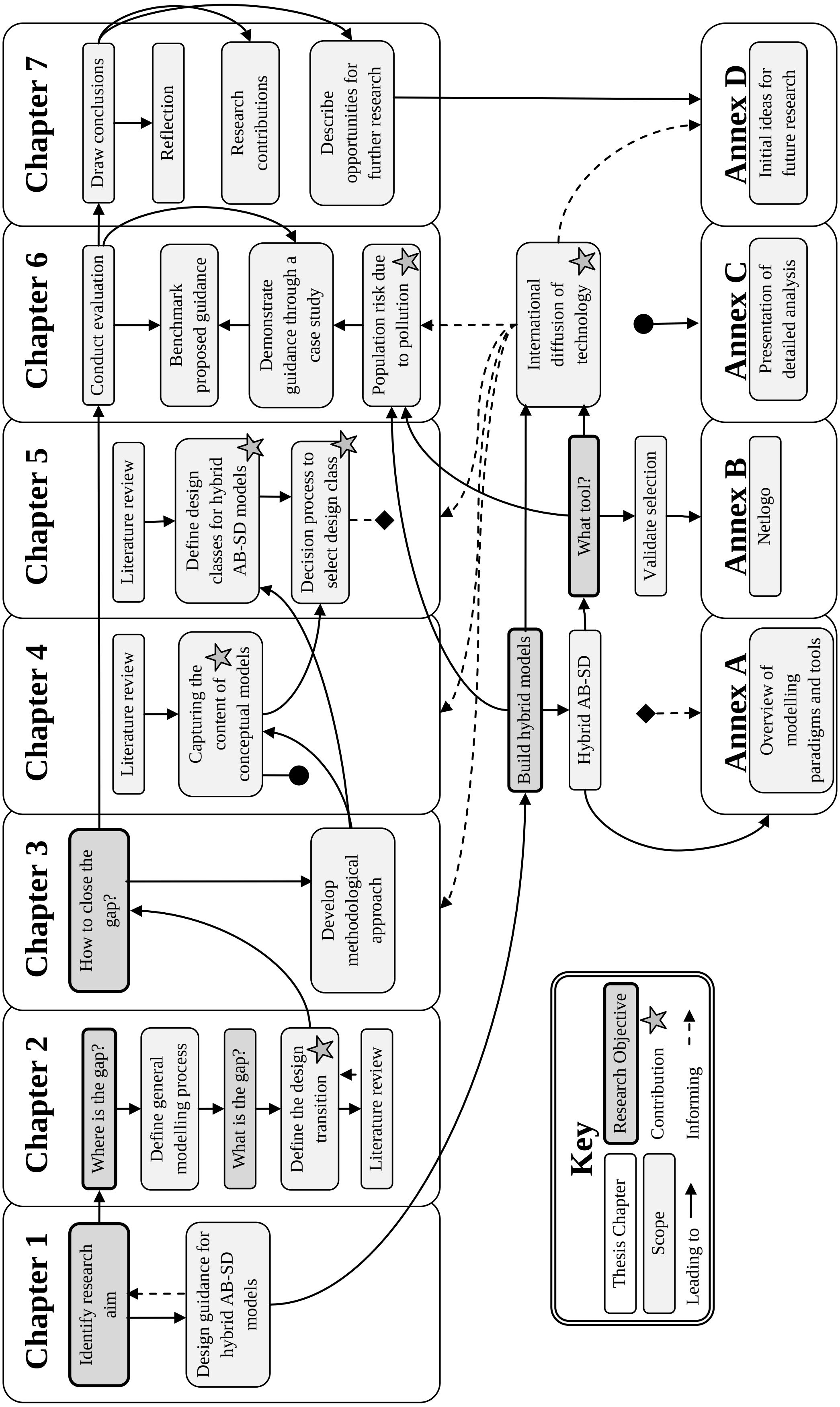

Figure 1-1: Overview of research objectives and scope

Having identified the broad aim of this research in Chapter 1, this thesis is structured to reflect the research undertaken to address a number of research objectives (dark-grey boxes in Figure 1-1). In Chapter 2 a general modelling process and the role of design within it are defined. Against these definitions, the research gap is confirmed through literature review, using a specific definition of the design transition (which is proposed as a research contribution highlighted by a star in Figure 1-1).

Chapter 3 considers the research objective: how to close the gap? The research methodology used is described and, subsequently, implemented in Chapters 4 and 5. This research is evaluated in Chapter 6, firstly through a case study to demonstrate the implementation of the general guidance derived in Chapters 4 and 5, and then through benchmarking to compare this research with other contributions reported in the literature. Chapter 7 concludes the thesis with reflections on what has been achieved, a discussion of the research contributions made (highlighted in Figure 1-1 using stars) and it presents some opportunities for further research.

Chapter 2 LITERATURE REVIEW

The objective of this chapter is to establish the specific research gap being addressed. Initially, the general modelling process is considered in order to establish where design guidance should be targeted. Within the context of a defined modelling process, the design transition is then defined and used as the basis to critically review the published literature. This identifies the specific research gap that this thesis looks to address.

2.1 The Roles of Modelling and Simulation

Modelling and simulation in support of decision making goes back hundreds of years (Holland, 1998). Building a model of a system and then running simulations with that model ("to trace through time" (Forrester, 1961, p. 52)), to investigate behaviours or characteristics of interest, go hand-in-hand; a common occurrence in management science as described by Pidd (2004), for example. Simulation modelling helps to visualise what might be or what has been, providing a means for communicating theories and insights and, importantly, engaging others who are involved in the decision making process. Without being able to visualise the problem, which contextualises the decision to be made, then it becomes more difficult to gain buy-in to a proposed solution; especially where commitment is required from others. Incorporating the Conceptual Model (Sargent, 1979; Robinson, 2012), discussed in detail later, these general concepts are brought together in Figure 2-1 to represent the roles of modelling and simulation in support of decision making. Decision making sits at the heart of this process, which is not explicitly recognised in other representations of the modelling process (i.e. Sargent, 1979 and Robinson, 2012). The views of Lorenz and Jost (2006) and of Chahal, Eldabi and Young (2013), who reiterate the view of Pidd (2004), supports the framing of the conceptual model by both the decision to be made and the problem being considered. This is important, as will become evident later in this thesis, as the bounding of the model specification must reflect both of these views; a model out of context or a model that does not address the decision to be informed is a design error.

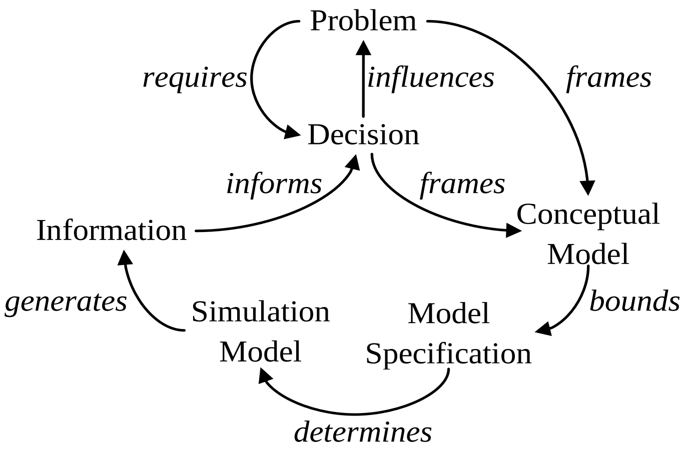

Figure 2-1: A general modelling process in support of decision making

The model specification determines the implementation of a specific simulation model: many specification-compliant models can be generated using different modelling techniques and computer platforms, for example. Through simulation, the model generates information about the core dynamic behaviour of the real-world problem. That information is used to inform the decision to be made which, in turn, can directly or indirectly influence the problem. This either solves the problem, at which point this process stops, or leads to another real-world problem.

Computer simulation itself, however, "is no panacea" (Pidd, 2004, p. 9): there may be more efficient and effective ways to resolve a problem and make decisions. The creation of a model is an investment in time, money and resources. However, this investment might be cost-effective for option exploration and replication, providing a legal basis for decision making or, as the only viable option, to gain insights such as where safety is an issue, for example (Pidd, 2004). Ultimately, simulation modelling and the associated modelling process provide opportunities to visualise the implications of decisions, helping to reduce risk and uncertainty.

Both Robinson and Sargent define a general modelling process. Robinson uses his definition to describe conceptual modelling (Robinson, 2012), whilst Sargent focuses on relationships with verification and validation (Sargent, 1979; 2007; 2013). In his description of the modelling process, Robinson bounds problem and model domains. Sargent, on the other hand, bounds Real and Simulation Worlds. Whilst there are strong associations between both views, there are, as might be expected given their different foci, also differences. Relative to the introduced roles of modelling and simulation defined in Figure 2-1, the general modelling processes according to Robinson and Sargent are presented in Figure 2-2 and Figure 2-3 respectively. The link from computer model to real world (problem) in Robinson's representation is dashed as the computer model is fit only for a specific purpose within the real world, it is not a model of the whole world and is based on simplifications and assumptions.

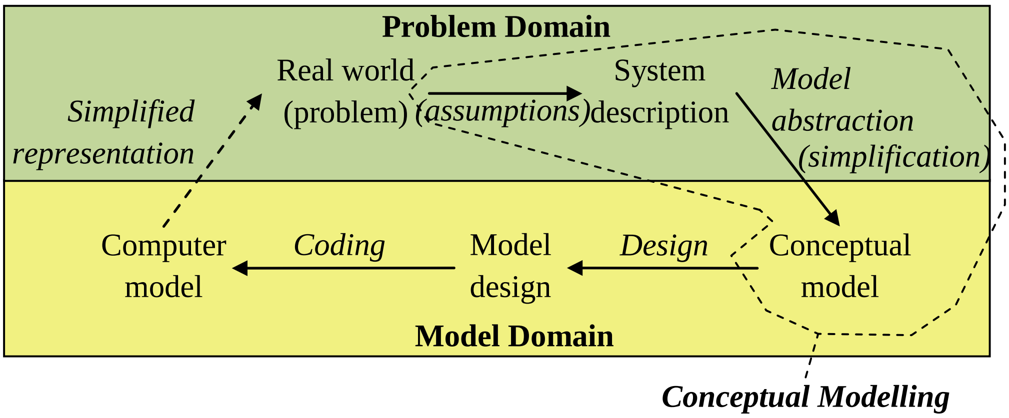

Figure 2-2: Artefacts of Conceptual Modelling (Robinson, 2012) (reproduced with permission: John Wiley and Sons RightsLink® licence – 3227570567323)

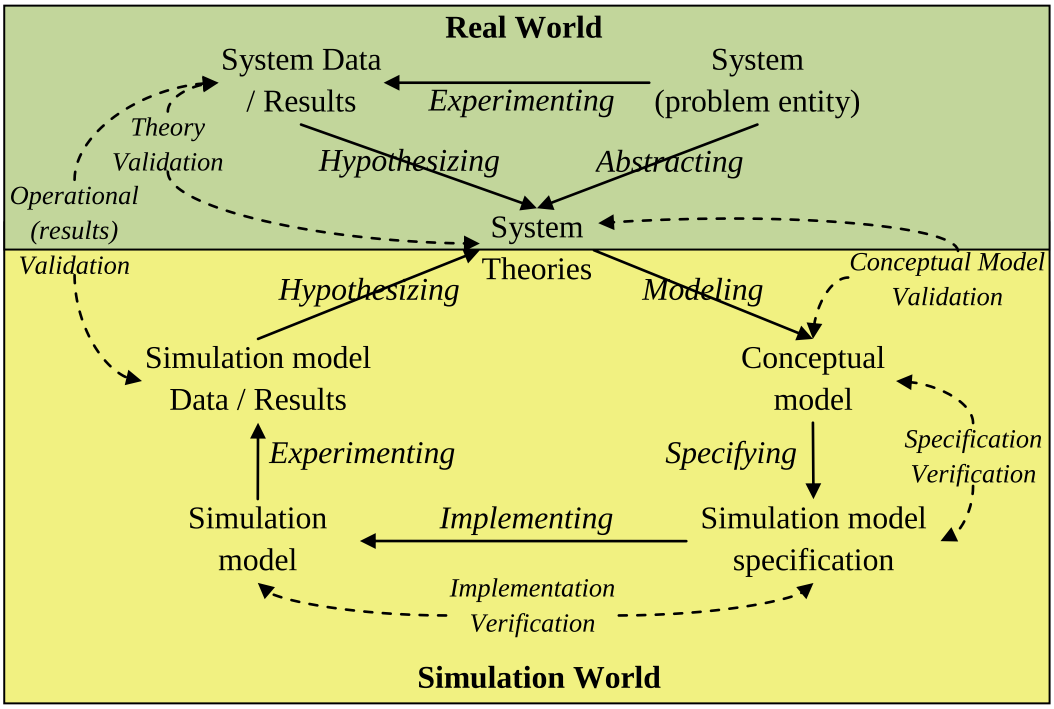

Figure 2-3: Real World and Simulation World relationships with verification and validation (Sargent, 2012)

In Figure 2-4 these 'world-views' are brought together; comparing Figures 2-1, 2-2 and 2-3.

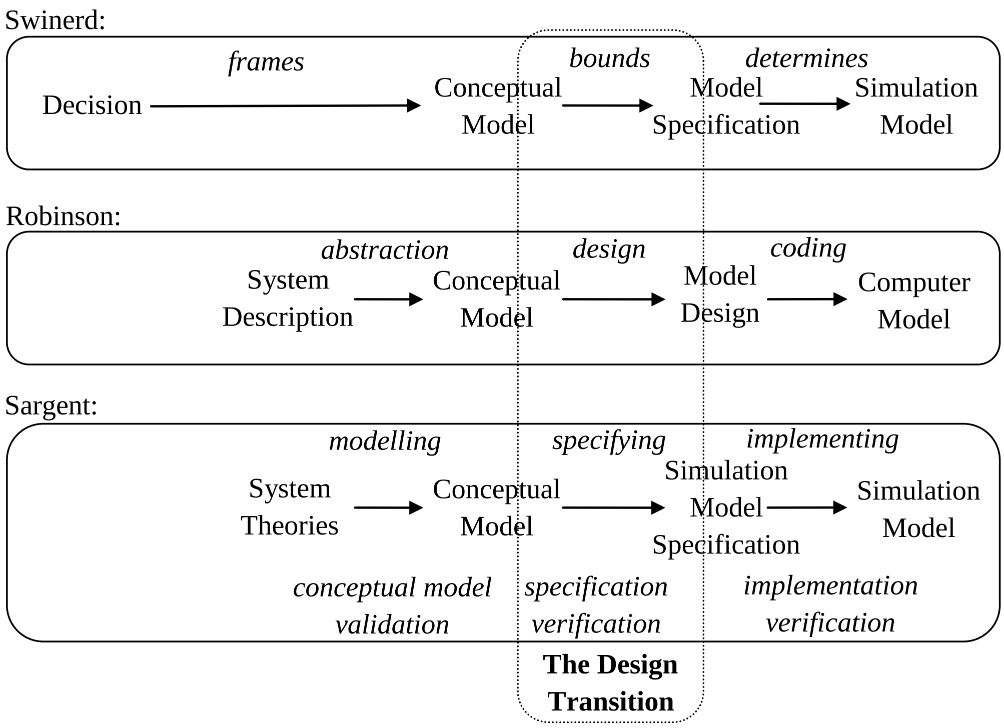

Figure 2-4: Comparing representations of the general modelling process

It is clear that the conceptual model provides a common reference point linked to specifying a model. Laying out the underlying theory for the model, agreeing what is in and what is out of the model and conceptualising the model with others remains an important aspect of the computer modelling process (Robinson, 2012). Recognising that the modelling process is iterative, the transition from (to) the conceptual model covers design and specification. It is this transition that is the focus for this thesis; it is here that both model design and utility of model designs are in sharpest focus. Recognising the design transition is important as it defines where design guidance brings most benefit, bounding model specification. The next objective is to define the design transition and then use that definition to identify the specific research gap.

2.2 Recognising the Design Transition

As Robinson (2012, p. 1) points out, "one of the most difficult issues in simulation modelling is determining the content of the simulation model." Within the general modelling process, conceptual modelling underpins the design process and is based on both assumptions and simplifications of the system to be modelled. Robinson (2012) proposes that conceptual models are always generated even if not formally captured and written down. Once created, he suggests that it becomes a persistent artefact living beyond the lifetime of studies or the computer model itself; even if only in the mind of its creator(s).

Validation of the model produced for simulating the system is formally related to the design process and hence to conceptual modelling as illustrated by Sargent (2007). The aim of conceptual modelling is to develop an appropriate model whilst validation aims to show whether the developed model is appropriate (Robinson, 2012). The focus for the review presented in this chapter is the transition between (from) conceptual modelling and (to) model design or model specification; titled 'design' and 'specification' by Robinson and Sargent, respectively. For ease of reference, this transition is termed the 'design transition' as specification, meaning the detailed description of a design, is part of the design process. The design transition is highlighted in Figure 2-4.

In order to critically analyse the design transition of the general modelling process, however, a formal definition was required. Here, the British Standard for systems engineering, which replicates exactly the international standard ISO/IED 15288, is utilised. The stated application for this internationally accepted standard applies to all man-made systems including (INCOSE, 2011, p. 1) "one-of-a-kind systems, mass-produced systems and customized, adaptable systems." Given computer simulation models can range from simple one-off systems to complex, enduring assets, these standards are taken to apply in all cases. According to the International Council on Systems Engineering (INCOSE) in their handbook for systems engineering (INCOSE, 2011, p. 21), "every man-made system has a life cycle, even if it is not formally defined"; a strong analogy to the comments of Robinson in respect to the existence of conceptual models. The international standard for systems engineering life cycle processes provides "a common process framework covering the life cycle of man-made systems" (The British Standards Institution, 2002, p. vi), which includes computer simulation models.

The generic life cycle includes the stages of (INCOSE, 2011): concept, development, production, utilisation, support and retirement. As well as the inclusion of decision gates to control progress through the life cycle, technical, project, enabling and agreement processes are also defined. According to INCOSE (2011, p. 21), "the purpose in defining the system life cycle is to establish a framework for meeting the stakeholders' needs in an orderly and efficient manner." They go on to state that "skipping stages and eliminating 'time consuming' decision gates can greatly increase the risks (cost and schedule) and may adversely affect technical development as well." By analysing the design transition of the general modelling process against these standards, the technical development of computer simulation models, from concept to production (implementation), can be critically reviewed. In doing so, not only is the technical approach to design enhanced, but project risk is further mitigated.

In order to position this chapter, the works of Robinson and Sargent are often cited. A search of the Scopus™ database (Elsevier B.V., 2013) for publications on conceptual modelling[1] provides 31 returns. When ordered by number of citations, the works of Robinson hold the top three positions. Equally, a search for verification and validation[2] provides 165 returns. Whilst the work of Kleijnen (1995) is the most cited, five publications by Sargent are represented in the top ten with the combined number of citations outstripping the other researchers. It is reasonable, therefore, to use the works of Robinson and Sargent, framed in international standards, to illustrate the level of published guidance covering the design transition for hybrid simulation models.

In Figure 2-5, the general modelling process as described by Robinson and Sargent, (Robinson, 2012, p. 6; Sargent, 2007, p. 127), has been mapped[3] to the (boxed) INCOSE generic life cycle.

[1] Scopus™ search: TITLE((“conceptual modeling” OR “conceptual modelling”) AND simulation)
[2] Scopus™ search: TITLE(verification AND validation AND simulation)
[3] The wording used in Figure 2-5 reflects a considered combination of that used by Robinson and Sargent.

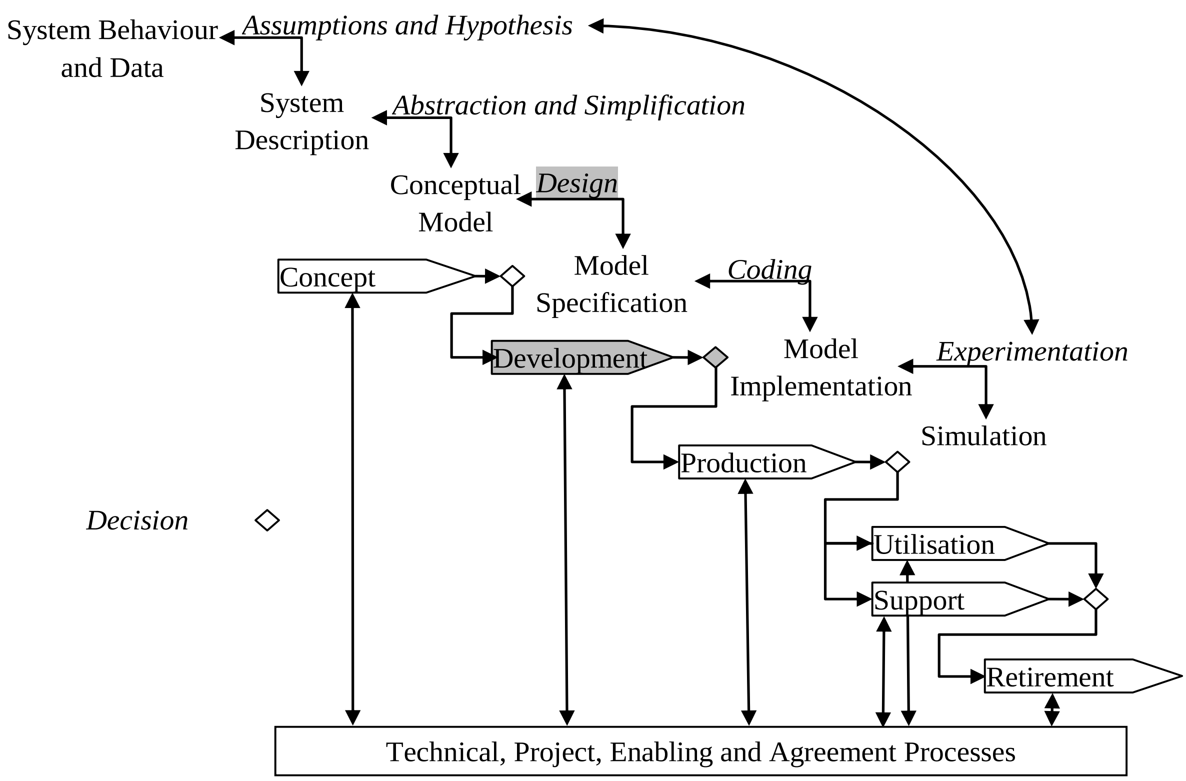

Figure 2-5: Mapping the general modelling process to the INCOSE generic system life cycle

Whilst the INCOSE systems engineering guidance considers a system and system elements, here the focus is hybrid models and modules. Modules are implemented in a single modelling paradigm and hybrid models built with modules, with at least two different modelling paradigms included in the design: models are equivalent to systems; modules are equivalent to system elements. As illustrated in Figure 2-5, the concept stage, the start of the INCOSE generic life cycle for systems, aligns with the system description and conceptual modelling artefacts of the general modelling process. The development stage aligns primarily with the design transition and concludes in the model specification artefact. As represented, a decision gate is normally established to approve model specification prior to commitment to coding and model implementation through the production stage. Technical, project, enabling and agreement processes are defined that are used as required to support the generic system life cycle.

2.3 The General Modelling Process within a System Life Cycle

Whilst there are no hard and fast rules, INCOSE provide an estimate of the level of effort relevant to each process at each stage of the generic life cycle. From this estimate, (INCOSE, 2011, p. 26), it can be seen that the application of technical processes is significant during the development stage and, therefore, important when reviewing the design transition. Drawing from the British Standard for systems engineering the technical processes are introduced in Table 2-1 with a brief description of the purpose of each; (The British Standards Institution, 2002, pp. 22-37).

Table 2-1: Synopsis of the technical processes defined within the ISO/IED 15288 international standard for systems engineering

Technical Process	Summary of Purpose
Requirements Definition	Define through-life system requirements for services in a defined environment.
Requirements Analysis	Convert requirements of desired services into technical product that could deliver those services.
Architectural Design	"Synthesize a solution that satisfies system requirements." (p. 27)
Implementation	"Produce a specified system element." (p. 29)
Integration	"Assemble a system that is consistent with architectural design." (p. 30)
Verification	"Confirm specified design requirements are fulfilled by the system." (p. 31)
Transition	Establish capability to provide required services in the operational environment.
Validation	"Provide objective evidence that services provided by the system when in use comply with requirements." (p. 33)
Operation	"Use the system in order to deliver its services." (p. 34)
Maintenance	"Sustain the capability of the system to provide a service." (p. 36)
Disposal	"End the existence of a system entity." (p. 36)

Before considering further the association between the design transition of the general modelling process and the technical processes for systems engineering, the life cycle to be used as the vehicle for facilitating a structured review is required.

A number of life cycle models exist such as waterfall, spiral and 'V' for example. The 'V' model has a particular focus on the "concept and development stages" of the generic life cycle (INCOSE, 2011, p. 27) and so is of particular relevance here. Through a review of the literature, Kasser (2010), identifies the first reference to the V-diagram, aka 'V' model, to be by Rook (1986) with respect to controlling software projects and being referred to as "the stages in software development confidence." The actual history of the 'V' life cycle model is not clear, although the growing complexity of computer science from the 1950s onwards and recognition of the need for formal software engineering are well documented; see, for example, the first IEEE Transactions on Software Engineering (Yeh, 1975). In considering software verification and validation, Mazza, et al. (1994, p. 71) state: "Software verification is both a managerial and a technical function, since the verification programme needs to be both defined and implemented." They then use the 'V' model life cycle to define the verification approach. With a demonstrated pedigree and application in managing software projects, the 'V' model is an appropriate vehicle for conducting this analysis. As confirmed by Mazza, et al. (1994), a fundamental feature of the 'V' model is that it is balanced with verification and validation plans explicitly identified between each arm of the 'V'; see also (INCOSE, 2011).

In Figure 2-6, the general modelling process described by Robinson (see Figure 2-2) and Sargent (see Figure 2-3), and summarised in Figure 2-6, has been framed[4] within the 'V' model. The arms of the 'V' are nominally aligned with modelling and simulation, both as a function of time running left to right, and hence maturity of the modelling process. As shown in Figure 2-6, the general modelling process comprises artefacts linked by transitions. These artefacts are represented along the modelling branch of the 'V' and transitions are represented in italic text down the centre of the 'V'.

Whilst the modelling processes described by Robinson and Sargent generally agree, there are some differences which have been abridged by the author in this representation. The principal benefit for doing this is that the position of artefacts within the general modelling process

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[4] The wording used in Figure 2-6 reflects a balanced combination of that used by Robinson and Sargent.

relative to plans for verification and validation can be clearly identified in an established format.

As Robinson (2012) suggests, the general modelling process is iterative in that the modeller can jump between artefacts of the modelling process and not necessarily in order. This is not well portrayed in the 'V' model for which alternative life cycle models could be used, however, the aim here is to analyse specific details of the design transition and not the specific nature of project management or implementation. The time axis could be shown wrapping around on itself as enhanced understanding of the system and its behaviours through simulation and experimentation can lead to refined system description, iterating as necessary.

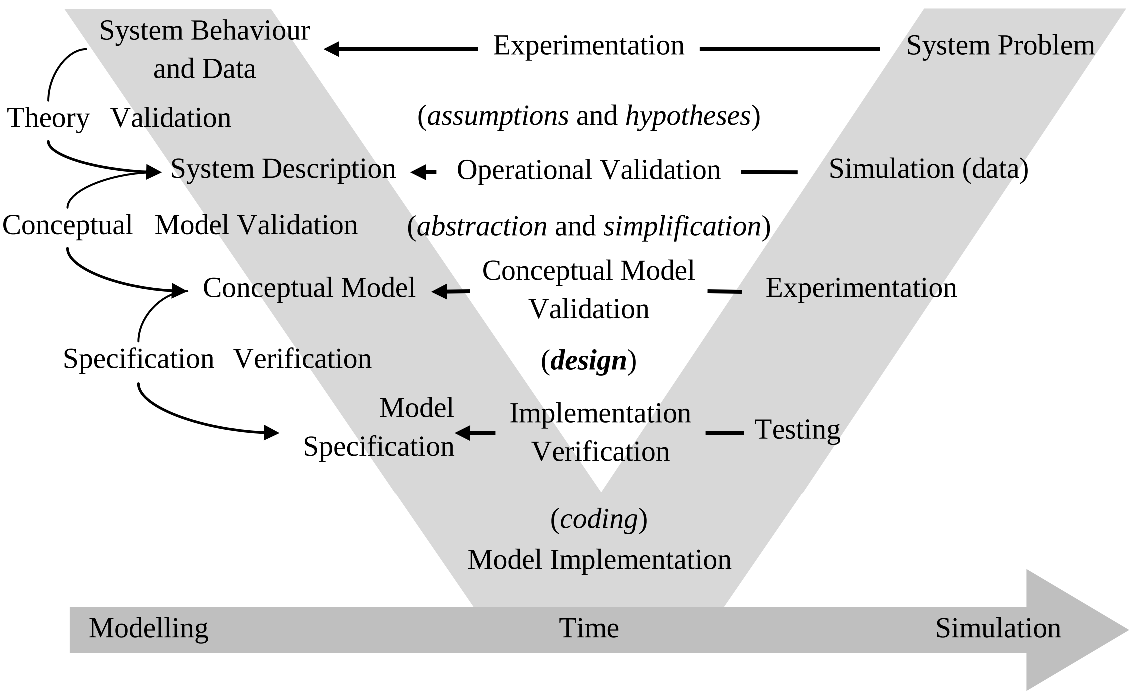


Figure 2-6: Framing the general modelling process

Having set the general modelling process against a formal system life cycle, the associations between the technical processes summarised in Table 2-1 are now compared to the conceptual modelling and model specification artefacts and the design transition that links them. The key phrases used by Robinson (2012) in his definition of a conceptual model and those used in the general modelling process by Robinson and Sargent are used in mapping these associations.

Both Robinson and Sargent agree that the conceptual model is the starting point from which the design transition starts. Robinson (2012, p. 13) defines a conceptual model as: "… a non-software-specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions and simplifications of the model." He associates objectives with the overarching study in which modelling is exploited and with the model itself. Study objectives capture aspects such as project duration and milestones, resources and customer requirements for example, whereas modelling objectives describe what the modeller is hoping to achieve with the model itself.

In most cases, it is straightforward to associate (or disassociate) the technical processes defined in Table 2-1 with descriptions for conceptual modelling and model specification. As defined by Sargent (2012) and represented in Figure 2-6, the design transition explicitly includes, or at least is coincidental with, specification verification, i.e. verification that the specification of the model to be coded, correctly conforms to the defined conceptual model. Less well defined but also central to the design transition, is the process of representing the content of the conceptual model, both "what to model" and "how to model" (Robinson, 2012, p. 6), in the model specification. These relationships are highlighted more clearly in Figure 2-7 which isolates the design transition in Figure 2-5 and 2-6 and the mapping to technical systems engineering processes presented in Table 2-1. Analysis of the general modelling process revealed that conceptual modelling was linked to model specification and that specification verification also linked these 'artefacts'. This has been refined using the INCOSE standards for systems engineering in order to draw out more precisely what takes place during this transition. However, this definition can be further refined bringing greater fidelity to the subsequent analysis of reported research that describes or reports on this transition.

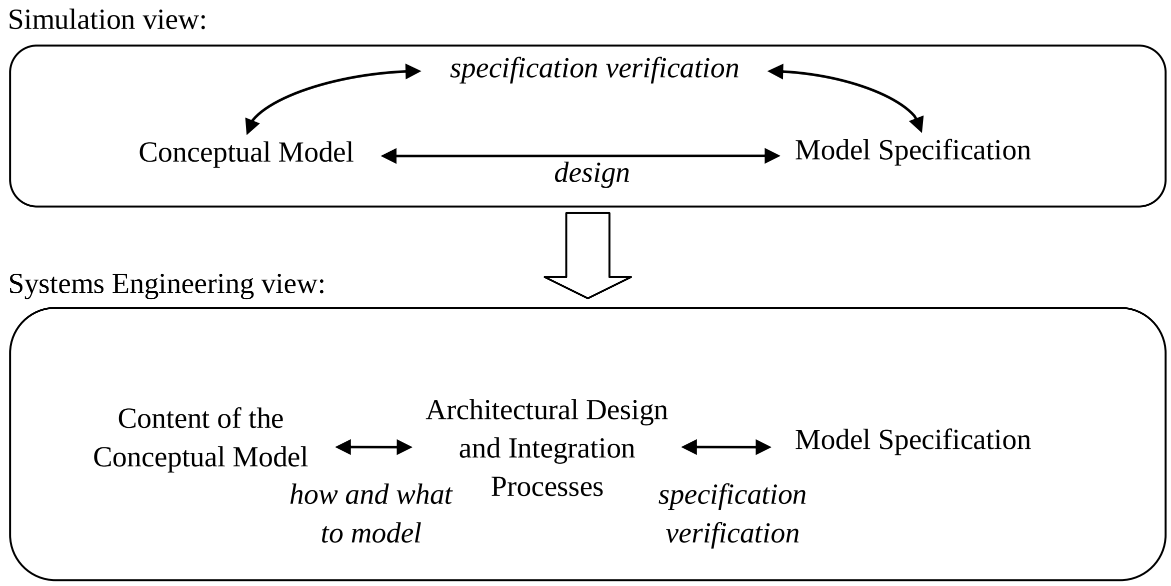


Figure 2-7: Initial clarification of the design transition

In a review of simulation inaccuracies, Robinson (1999) identifies sources for error in modelling, in the data, and in experimentation. Under modelling, he identifies poor understanding of the original problem, poor conceptual modelling and poor translation from conceptual model to computer model (defined as simulation model here) as the primary sources for simulation errors. The analysis presented here, formally defines the transition from conceptual model to model specification and hence, could be a useful aid in reducing simulation errors as described by Robinson (1999) with respect to translational errors. Whilst focussing on ABS, research is reported for automated translation from conceptual model to simulation model (Cetinkaya and Verbraeck, 2011; Rioux and Lizotte, 2011) using metamodelling techniques. They too refer to and look to address reducing translation errors.

2.4 Architectural Design and Integration

Each process defined by INCOSE in their systems engineering handbook is described in the same format detailing inputs and outputs along with enablers and controls. In Table 2-2 the inputs and outputs only for the technical processes of Architectural Design and Integration are summarised as these reflect the primary aims of each.

Table 2-2: Inputs and outputs for the INCOSE technical processes of Architectural Design and Integration

Inputs	**Outputs**
Architectural Design Process	
Concept Documents	Technical Performance Measure Needs
System [*Model*] Requirements	Technical Performance Measure Data
System [*Model*] Functions	System [*Model*] Architecture Description
System [*Model*] Functional Interfaces	Interface Requirements
Specification Tree	System Element [*Module*] Requirements
System [*Model*] Specification	System Element [*Module*] Descriptions
Requirements Verification and Traceability Matrix	System Element [*Module*] Requirements Traceability
System [*Model*] Requirements Traceability	
Integration Process	
Interface Requirements	Integration Strategy
System Elements [*Modules*]	Integration Enabling System [*Model*] Requirements
System Element [*Module*] Descriptions	Integration Constraints on Design
System Element [*Module*] Documentation	Integration Procedure
Accepted System [*Model*]	Integrated System [*Model*]
	Interface Control Documents
	Integration Report

Firstly, it can be seen that some outputs from the Architectural Design process are inputs to the Integration process, i.e. module descriptions. Secondly, the content of these processes can be summarised as comprising five elements: technical performance; architectural description; interfaces; integration and module definition.

This analysis has condensed the design transition into essential elements and is finally clarified in Figure 2-8. The design transition translates the ‘how and what’ from the content of the conceptual model to model specification using architectural design and integration processes and techniques for specification verification.

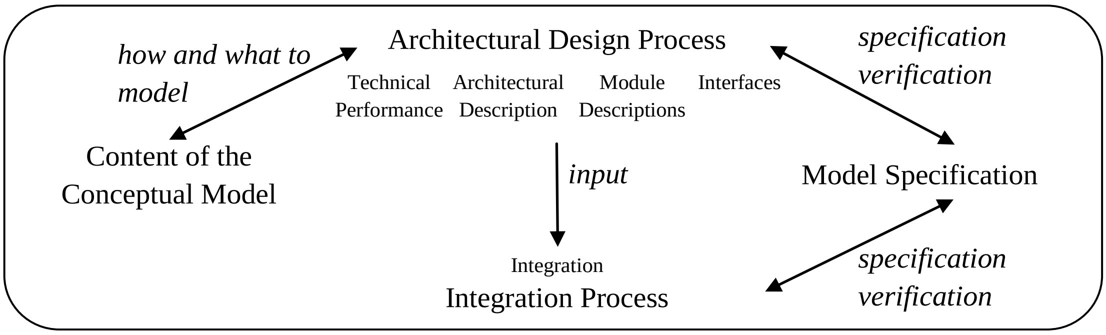


Figure 2-8: The design transition

This definition of the design transition is used to review the literature to establish whether there is a gap in knowledge or not and, if so, meet the research objective to specifically define that gap.

Although research is reported on transformation, including automated translation, of conceptual models to simulation models (Cetinkaya and Verbraeck, 2011; Onggo and Karpat, 2011; Roux and Lizotte, 2011) and with the possible exception of Sargent's work (1979; 2007; 2012) on verification and validation of simulation models, there is little reported that brings together these disciplines of modelling and simulation and engineering. This new definition of the design transition using a systems engineering approach is, therefore, proposed as a research contribution.

2.5 Literature Review: Is the Design Transition appropriately described?

Publications that discuss a multi-paradigm approach to modelling and simulation can generally be broken down into two groups - those that consider methodological issues, and those that look to use a hybrid model to solve a problem. Increasingly, the focus for publications that discuss the hybrid AB-SD combination, the primary focus for this literature review, has turned towards problem solving.

Early works published in the 1990s used problem solving as a basis to start to explore method and design for SD models influenced by ABS design principles, e.g. Table 2-3. Publications then tended to address method and the correspondence between modelling paradigms, e.g. Table 2-4, until recently where the focus is mainly problem solving, e.g. Table 2-5. This is perhaps a natural transition, starting out through early experimentation before stepping back to review the wider principles at play before finally settling into application guided by the identified principles. The next three sub-sections provide a review against this general background. In sub-section 2.5.1, the early works that primarily considered the influence of ABS modelling on SD modelling are discussed. In sub-section 2.5.2, the correspondence between the two modelling paradigms is represented before, in sub-section 2.5.3, a range of problem solving publications are reviewed, drawn from a diverse range of research domains.

The primary aim of this literature review is to assess the level of coverage given to describing the design transition process, and especially the level of discussion relevant to each of the five elements identified previously for this transition. In conducting this review, it became clear that the literature reporting the use of hybrid modelling to solve problems provided most information about the design process and design transition in particular; even if not formally identified as such. This is not unsurprising as the aim of the other types of studies reviewed are more philosophical and not focused on the specific details of model building to address a specific problem: they are, however, reported for completeness. Each sub-section is summarised with a table that captures the author's view on the level of detail given to each of the five elements of the design transition. The means by which information is portrayed in the literature is summarised and a grey-scale colour code used to highlight, respectively, whether the design transition is not described (dark-grey), can be inferred from the text (light-grey), or is referred to explicitly (no shading).

2.5.1 Agent-oriented SD Modelling

With one or two exceptions, the majority of published works looking at the potential of hybrid simulation modelling and represented in this review, date from the 1990s. As can be seen from Table 1-1, this is the decade during which AB modelling was taking-off and so research communities were starting to note the potential for combining ABS with other modelling paradigms. With respect to SD, these early papers tended to consider the influence of agent-based modelling on SD model design and implementation. Sterman's 1985 publication describing his model of scientific revolution, as discussed in detail in Annex B, is an early example that raises the potential for hybrid modelling. This work led to a dialogue between Sterman and Wittenberg that culminated in their skilfully crafted 1999 paper. Their refined model is constructed using classical system dynamics stock-and-flow structures to represent scientific paradigms as agents stating that (Sterman and Wittenberg, 1999, p. 324): "unlike some agent-based models, the individual paradigms have a rich internal structure representing the activities of each community." Whilst each agent has the same internal structure, agents can rise and fall as the simulation progresses.

Akkermans (2001) recognised this approach for representing agents within a system dynamics simulation environment whilst drawing on ABS design principles in his paper describing emergent supply networks comprising independent firms represented as adaptive supply agents. In discussion, Akkermans states of this modelling methodology that (2001, p. 8): "it appears feasible, and even advantageous, to implement agent-based models in a system dynamics environment." The paper also draws out some limitations with this approach such as (2001, p. 8) "the agents in this model do not breed, nor is there rule discovery", contrasting the model against the stated requirements defined by Holland (1998) for representing agents within complex adaptive systems, namely: "the reaction ability"; "the adaptation ability"; and "the ability to evolve". It is worth noting, however, that Sterman and Wittenberg appear to have represented breeding, or at least emergence and life-span, and rule discovery in their model. The self-proclaimed limitations of the Akkermans' model in this respect may, therefore, not necessarily be limitations to using AB modelling principles within the design of a system dynamics model, referred to hereafter as ‘agent-oriented SD’ modelling.

Phelan (1999) draws on the work of Vriend (1994) who had built an agent-based representation of an economy where the firms (agents) were able to grow or decline over time as opposed to previous models where firm size had been assumed homogenous. He observes that a combination of chance conditions exploited by rapid learning led to some firms becoming more successful than others, even though they started equal. The work of Sterman and Wittenberg demonstrates that such growth and decline can also be modelled in an agent-oriented SD simulation. These examples, written at the time when publication rates for ABS modelling were just starting to take-off, provide early evidence of influence between different modelling paradigms; here the influence of ABS on SD model design.

Duggan (2007) later extends the potential for continuous agent-oriented SD modelling, looking to provide an equation based modelling approach for large scale heterogeneous agent societies. Through a case study of market dynamics, he demonstrates this modelling concept which includes a spatial neighbourhood model, in which agent location relative to the other agents is represented. This spatial representation as well as the opportunity to represent large numbers of agents extends the agent-oriented SD modelling approach of Sterman, Wittenberg and Akkermans.

Whilst these examples all look to build and define a form of hybrid simulation model, they are all implemented in a single modelling paradigm (SD) and, consequently, cannot provide detailed insight into all of the five elements identified for the design transition. Whilst some do provide good information in regards to technical performance, architectural descriptions and interfaces, the use of a single paradigm limits insights for models that could incorporate more than one modelling paradigm; especially when defining modules and their integration. The summary for this component of the review is presented in Table 2-3

Table 2-3: Assessment of agent-oriented SD literature against the five elements of the design transition

Publication	Technical Performance	Architectural Description	Modules	Interfaces	Integration
Sterman (1985); Steman and Wittenberg (1999)	Explicit: well described aided by causal diagrams and test results	Explicit: Figure 1 model structure	Explicit: single paradigm	Explicit: causal diagrams	Single paradigm
Akkermans (2001)	Explicit: well described aided by causal diagrams and test results	Explicit: Figure 1 structure provides outline	Explicit: single paradigm	Explicit: causal diagrams	Single paradigm
Duggan (2007)	Explicit: causal diagrams and embedded equations	Explicit: Figure 1 conceptual design	Explicit: single paradigm	Explicit: equations	Single paradigm

Key	Not Described	Described Explicitly	Can be inferred

2.5.2 On the Correspondence between ABS and SD Modelling

Phelan and Scholl published a number of articles between 1999 and 2001 in which they discuss the correspondence between deductive SD and inductive ABS approaches to modelling. Phelan (1999) associates rationality with careful observation combined with deduction and induction in order to reveal 'reality'. There is good agreement between this view and that proposed earlier by Lane (1994, p. 118) who states: "If we seek to operate in the real world, it is surely better to have available a range of approaches and tools that draw on the breadth of systems thinking." In comparing complexity theory to systems theory, associated with agent based and system dynamics modelling, respectively, Phelan identifies three areas of noticeable difference. Firstly, the agenda for complexity theory is exploratory as opposed to confirmatory with systems theory. The modelling techniques are different, ABS versus the "circular flows" of SD, and finally, the theory of method (epistemology) focuses on emergence from simple interactions rather than careful and holistic understanding of the structures of a system.

The dialogue between Scholl and Phelan then explores the benefits of analysing the same problem with different approaches, especially with the theories of complexity and systems. Drawing on the work of Holland (1999 cited in Scholl 2001b, p. 14) Scholl notes: "interdisciplinary comparisons allow us to differentiate the incidental from the essential. When we look for the same phenomena in different contexts, we can separate features that are always present from features that are tied to context."

Scholl proposes to model well known problems drawing from both disciplines such as the Beer Game in SD and predator-prey scenarios in ABS, for example. As reinforced by their conclusions from their joint publication (Scholl and Phelan, 2004), they propose that the benefits of this are realised in gaining a deeper understanding of the problem, cross-validation and triangulation of results; Mingers and Brocklesby (1997) note the early use of triangulation using a mixture of research methods in sociology.

In considering metaphor and innovation, Holland (1998) discusses the process of translation from a source model to a target model:

"*The mechanisms of Maxwell's imaginary fluid, his source, must be related to the less*-*well-understood mechanisms of his target, electromagnetic phenomena. This correspondence between mechanisms provides a translation that brings the source's aura of technique, consequences, and interpretation across to the target*."

Holland (1998, p.207)

Here, Holland is proposing that by linking from a well understood, or at least accepted, source to a new, little understood, target, that the body of knowledge and credibility of the source might be mapped to the target. This is akin to the correspondence between well-known SD and ABS paradigms to the emerging hybrid AB-SD modelling approach.

A focus of this early dialogue between ABS and SD modelling was in the use of one to confirm the validity of output with the other, to triangulate output. As a result, they consider the interfacing of model output where the models themselves are written in different modelling paradigms, although this does not extend to the detailed interfacing of paradigms. As would be anticipated, the technical performance of these models is well described but there is no guidance given for the other elements of design transition. This is probably because these studies do not consider truly hybrid models, i.e. models built with more than one modelling paradigm.

As cited in Annex A and confirmed by Gröβler, Stotz and Schiertz (2003), Schiertz and Milling discuss principal methodological issues differentiating SD and ABS approaches (Schieritz, 2002; Schieritz and Milling, 2003). Through this work, they look to opportunities for integrating the two modelling approaches through supply chain management (Schieritz & Gröβler, 2003) and latterly population dynamics (Schieritz and Milling, 2009); their hybrid models are included in the review of sub-section 2.5.3.

Most recently Lättilä, Hilletofth and Lin (2010) consider when, why and how hybrid AB-SD simulation models might be used as expert systems. Usefully, their literature review confirms that undertaken for this thesis, although their focus is not on the underlying design transition as is the case here. Based on their review, they identify five methods used for creating hybrid simulation models: low-level programming; SD programming; SD with middleware; hybrid toolset; or constructing simulation software. Whilst their review informs the general modelling process for hybrid models, it does not provide any detailed insight into the specific elements of the design transition.

Table 2-4: Assessment of literature that discuss the correspondence between SD and ABS against the five elements of the design transition

Publications	Technical Performance	Architectural Description	Modules	Interfaces	Integration
Phelan (1999); Scholl (2001a); Scholl (2001b); Scholl and Phelan (2004)	No detail	Focus on separate paradigms	Single paradigm	Descriptive: Model output	Single paradigm, triangulation of outputs
Schieritz (2002) Gröβler, et al. (2003) Schieritz and Milling (2003)	Descriptive: Introduction	Explicit: Early concepts especially micro SD within macro ABS models	Descriptive: Introduction to concepts with focus on differences between paradigms	Explicit: Concepts and low level detail for interfacing modelling tools	Potential concepts
Lättilä, et al. (2010)	Descriptive: Introduction	Not covered	Descriptive: Introduction	Not covered	Descriptive: Five methods summarised

Key			Not Described	Described Explicitly	Can be inferred

2.5.3 Hybrid Simulation Models

The studies reviewed here draw from a diverse range of research domains covering the period 1999 to 2013. Whilst this may not be an exhaustive review, it does serve to highlight the general level of attention given to the design transition when reporting on hybrid models and the application of this class of model. A top-level summary of reporting against each of the five elements for design transition is provided in Table 2-5. Within this table, summaries of the interfacing of modules is categorised as either ‘sequential’, ‘interfaced’ or ‘integrated’. These terms represent design classes (Swinerd and McNaught, 2012a) that will be fully introduced in Chapter 5. For now, it should be noted that in a sequential design, information flows from one module to another in strict order. In an interfaced design, modules do not interact at all but the output from them is combined to provide the final model output. Finally, an integrated design has modules with continuous information flow between them, including feedback.

Table 2-5: Assessment of a number of published hybrid AB-SD models against the five elements of the design transition

Publication	Technical Performance	Architectural Description	Modules	Interfaces	Integration
Homer (1999)	Explicit: causal diagrams	Descriptive: via SD causal diagrams	Explicit: SD strategy AB workforce training	Explicit: sequential	Explicit: via lookup table in SD module
Schieritz (2002); Schieritz and Gröβler (2003)	Explicit: causal and flow diagrams plus results analysis	Explicit: Figure 1	Explicit: micro SD company schema and macro AB supply chain	Explicit: integrated	Explicit: Figure 3
He, et al. (2004)	Explicit: equations	Explicit: general structure (Figure 1)	Explicit: SD land demand CA land supply	Explicit: sequential	Explicit: balance demand with supply
Dubiel and Tsimhoni (2005)	Descriptive: explanation	Descriptive: representing free movement within discrete system	Explicit: AB theme park DES tram	Descriptive: interfaced	Explicit: Figure 1
Chaim and Streit (2008)	Explicit: casual diagrams and fuzzy logic	Explicit: conceptual model (Figure 2)	Explicit: AB participants SD governance	Descriptive: integrated	Descriptive: not described in detail
Meza and Dijkema (2008)	Descriptive: explanation	Explicit: Figure 3	Explicit: AB actors with embedded SD decision making plus SD transition model	Explicit: integrated Figure 3	Explicit: example given in Figure 4 conceptual micro-meso-macro Figure 2
Gaube, et al. (2009)	Descriptive: supplementary information cited	Explicit: concept diagram Figure 1	Explicit: AB actors, GIS land use and SD socio-ecological modules	Explicit: integrated Figure 1	Descriptive: fundamental to design but no detail provided
Kieckhäfer, et al. (2009)	Explicit: equations	Explicit: Figure 6 plus description within framework for automotive case study	Explicit: Figure 6	Explicit: integrated Figure 6	Explicit: Figure 6 and equations
Verburg and Overmars (2009)	Descriptive: focus on land conversion and allocation	Explicit: Figure 1	Explicit: top-down allocation with bottom-up conversion	Explicit: integrated (c.f. figures 1 and 2)	Explicit: Figure 2
Schieritz and Milling (2009)	Explicit: description plus equations	Descriptive: noting case study used to demonstrate methodological approach	Explicit: SD population model supplemented by aggregate output from AB module	Explicit: sequential	Explicit: through table function of refined SD modelling approach
Zhao, et al. (2011)	Explicit: data and equations	Descriptive: background theory and research used to set scene	Explicit: AB high level adoption and AB + SD low level payback	Descriptive: integrated	Explicit: sequence diagram Figure 2
Shafiei, et al. (2012)	Explicit: equations Figure 1	Explicit: Figure 1	Explicit: Figure 1	Explicit: integrated Figure 1	Explicit: Figure 1
Swinerd (2012)	Explicit: equations and Figures 2 and 3	Explicit: Figure 2	Explicit: description plus Figures 2, 3 and 4	Explicit: Figures 2, 3 and 4	Explicit: Figures 2, 3 and 4
Nikolic, et al. (2013)	Explicit: each module described individually	Explicit: Figure 1 and specific sub-section	Explicit: each module described individually	Explicit: Figure 2	Explicit: Figures 1 and 2
Viana, et al. (2012)	Descriptive: at time of publication model in development	Explicit: Figure 1 conceptual architecture	Explicit: Figure 1	Explicit: integrated Figure 1	Explicit: Figure 2 as example plus supplementary information
Key			Not Described	Described Explicitly	Can be inferred

The results of this literature review reveal that most of the elements required to completely describe the design transition phase are generally included within publications. This is perhaps unsurprising as the authors are all practitioners of modelling and simulation reporting their work in this field. It is also recognised that editorial restrictions may limit the level of detail that can sometimes be reported. Those with good coverage across the five elements tend to do so via one or two diagrams, which may be a good approach where such limits apply; see Figure 4-10 - a replica of the first figure used by Shafiei, et al., (2012, p. 1075), which is a good example as it effectively represents all five elements of the design transition in one diagram.

Technical performance tends to be reported through combinations of detailed description, equations and formal method. Interestingly, architectural description tends to be represented diagrammatically (12 of the 15 publications) which is consistent with the review of agent-oriented SD models. It is also worth noting that in 7 of the publications included in this review, the diagram from which the architectural description can be derived is the first figure. This reinforces the importance of the design transition when reporting model design and application. The description of interfaces and integration similarly benefit from the use of diagrams with 8 and 10 publications including them, respectively. Without fail, modules are well described. This is perhaps unsurprising as the publications specifically report on the design and application of hybrid models and so clarity of which part of the problem is being modelled by which modelling paradigm and how they are interfaced and integrated is of primary importance.

2.6 Need for Guidance: The Research Gap

As might be anticipated, the design transition is described to a greater or lesser extent in all the publications reviewed that report on the design and application of a hybrid simulation model. Sitting between the conceptual model which, as already discussed, is always created, even if not written down, and model specification, the design transition is fundamental to the general modelling process and so it is no surprise that it is always described.

There is, however, little consistency when describing the design transition and, therefore, it is not straightforward to identify best practice or broad guidelines to assist in managing this transition for the benefit of future studies and model design. If the use of hybrid simulations grows as anticipated, then this gap in knowledge should be addressed in order to enhance the technical approach to modelling, facilitate efficiency in the general modelling process (supported by Lättilä, Hilletofth and Lin, 2010, p. 7974) and reduce project risk (e.g. reducing simulation errors (Robinson, 1999)).

Given that coverage of the design transition in the literature reviewed is good, there is an opportunity to capture this information and present it in a consistent and structured format. Based on the initial literature review presented here, any general guidance realised would best be captured diagrammatically as this is the most efficient and likely exploitation route to informing future studies and would assist researchers and modelling practitioners alike with editorial restrictions for publication.

2.7 Chapter Summary

In accordance with the aim of this research defined in Chapter 1, the research objectives of this chapter were to identify where design played a key role within the general modelling process and, having done this, to identify whether there was a gap in the knowledge to inform the design of hybrid AB-SD models.

The works of Robinson and Sargent were compared and a general modelling process defined, framed against the systems engineering 'V' life-cycle model; this model being well suited to the development phase of software projects. The design transition was identified linking conceptual modelling and model specification and incorporating specification verification.

Again turning to systems engineering, this design transition was defined, which, in itself, is proposed as a research contribution.

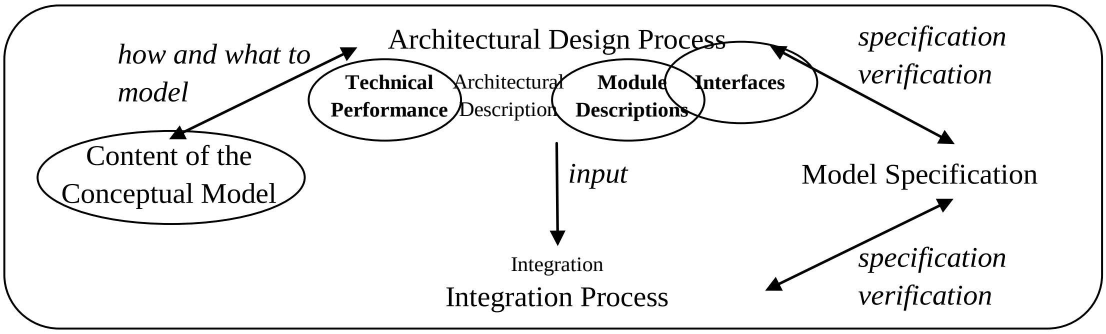
A critical review of the literature using this definition for the design transition confirmed the research gap for this thesis: that there is lack of general design guidance for hybrid AB-SD models. Whilst this gap was confirmed, it was also observed that a wealth of relevant information resides within the published literature, especially those publications that describe the implementation and application of models. It was postulated that this source of information could be used to address the confirmed research gap.

Chapter 3 RESEARCH METHODOLOGY

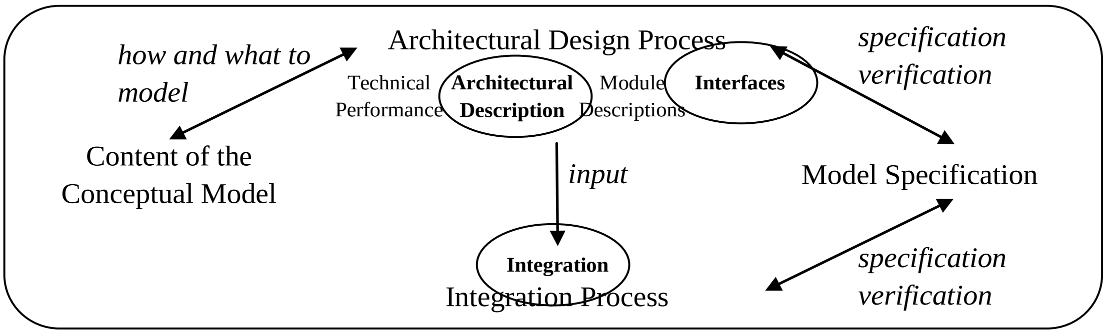
The objective of this chapter is to establish the methodology used to address the research gap identified in Chapter 2. Drawing on the works of Robinson and Sargent to confirm the general modelling process and associated plans for verification and validation, a systems engineering approach was used to uniquely define the design transition. Against this formal definition, a literature review was conducted to show the level and detail of reporting used to describe it.

Most insight was gained by reviewing publications that describe the design and application of hybrid models; as opposed to publications that consider philosophical aspects. In such publications, it was found that details of the design transition are typically reported either directly or might be inferred. Given that the design transition is a fundamental component of the general modelling process, it is perhaps unsurprising that all of the publications reviewed describe it to some degree. In itself, this observation serves to confirm the importance of this transition in the modelling process. However, this review demonstrates that there is no consistency and varying levels of detail make it difficult to distil clear guidance and examples of best practice that might be used in the design of future hybrid models. These findings establish the basis for the research methodology which will be used to address the research gap: to use an inductive approach, exploiting peer reviewed literature of applied hybrid simulation modelling. By intentionally drawing from a diverse range of application domains, it is further anticipated that generic guidance can be defined for the hybrid AB-SD modelling combination.

Drawing from the definition of the design transition highlighted in Figure 3-1, it is proposed that the content of the conceptual model determines the technical scope and capabilities of the model (problem context, physical units, insights required, etc.); how different modelling paradigms, and hence different modules (modules being implemented in a single modelling paradigm), might be used to represent aspects of the problem being modelled; and what interfacing is required between modules (the key interfaces and points of information exchange). The architectural design integrates this within a considered design for the hybrid simulation model. Between them, they totally describe the design transition.



(a) Capturing the content of conceptual models



(b) Architecting

Figure 3-1: Division of research focus for characterising the design transition

However, a method is required to establish a consistent approach to the literature review. Given the effectiveness of the method used for the initial review of the literature to establish the research gap, the use of defined frameworks is proposed. Defining frameworks limits the scope for being drawn into application specific details of a reported model, bounding the focus of critical review, in this case towards design. Frameworks are required for both capturing and representing the content of conceptual models and design classes for architecting (a design class being a categorisation of design archetype). As with the formal definition of the design transition used to conduct the initial literature review, these will also provide the basis for reviewing the literature in a consistent manner. The first step in each case, therefore, is to define these frameworks. The next step is to review the literature using them as a basis for deducing insight. Unlike the need to derive a definition for the design transition, there are opportunities to build upon the literature for the frameworks to capture the content of conceptual models and define design classes. The research to be drawn upon reports on the underlying construct of modelling techniques, which, when combined appropriately, are applied here to the analysis of hybrid AB-SD models.

The research conducted to capture the content of conceptual models (Figure 3-1(a)) is reported in Chapter 4 and then to architect this information is reported in Chapter 5 (Figure 3-1(b)).

In order to contextualise and evaluate this inductive research approach, it is also necessary to design and implement hybrid AB-SD models. This serves two purposes: firstly, to provide experiential insights during the observation and translation of the literature through the lenses of the frameworks and, secondly, to provide the opportunity to evaluate findings and the emerging guidance deduced from the literature. Whilst this evaluation approach is reported in Chapter 6, the influence of my own model building to inform the inductive research approach is not explicitly reported in Chapters 4 and 5.

3.1 Chapter Summary

The objective of this chapter was to outline the research methodology with which to address the research gap defined in Chapter 2. Drawing from the findings of the initial critical literature review, it was noted that a wealth of information resides within the published literature. This suggested that an inductive research method might be appropriate, looking to exploit the peer reviewed literature to draw out general observations.

Turning to the definition of the design transition, two aspects were identified. Firstly, that the content of the conceptual model would inform technical performance of a model, module descriptions and the principal interfaces between modules. Capturing this content in a consistent framework was, therefore, the first step. Secondly, having captured the content of the conceptual model in the manner described, to bring this information together in an architectural description that integrated everything into a coherent design.

These are the subjects of Chapters 4 and 5, respectively. Chapter 6 reports on the evaluation of the general design guidance derived using this methodology.

Chapter 4 THE CONTENT OF CONCEPTUAL MODELS

The objective of this chapter is to introduce a general framework for consistently representing the content of conceptual models. In Chapter 2 we confirmed that the conceptual model is the starting point for the design transition (Figure 2-8). Whilst all elements of the conceptual model were considered, it was also established that it is the content that mostly shapes the design transition. In order to build a thesis for the methodological guidance of the design transition, therefore, it is both necessary to identify the content of a wide range of conceptual models reported in the literature and to represent this content in a consistent framework.

Selected because of their analysis of the fundamental structure of simulation models and general agreement with observations from a wide range of other studies, the work of Parunak, Savit and Riolo (1998) is combined with that of Lorenz and Jost (2006) to provide a general framework within which the content of conceptual models can be represented. Based on Robinson's (2012) definition of a conceptual model, a form has been designed to aid a comprehensive assessment of the literature. As with the literature review presented in Chapter 2, the information gathered was either explicitly stated or required interpretation and so the results of this review are fully reported at Annex C. In each case, the content of the conceptual model is successfully represented in the proposed general framework.

From this, the definition of what constitutes elements in the context of the proposed general framework is provided and, drawing from standards for software engineering, the nature of the interfaces between elements of the framework are reviewed; between individuals, observables and the environment. Finally, the benefits of using the general framework to conduct verification and validation and especially to specification verification are discussed. Before developing the general framework, the hierarchy and coupling of components in real-world systems are considered. This is important as the framework should support the representation of both vertical and horizontal coupling seen in real systems (i.e. coupling between different and similar scales of the system).

4.1 Systems: Scale and Hierarchy

The range of systems modelled by computer simulation models is diverse. These systems are often complex, changing with time, in space and at different scales of hierarchy. Relative terms of scale are used in the literature to identify how a system is decomposed and represented within a model. Typical terms include: micro, meso or macro; individual or societal; heterogeneous or homogeneous; local or aggregate. Of increasing interest, and an area where hybrid simulation modelling may be shown to add value over and above single paradigm approaches, is the coupling between scales of systems. Coupling might be described as vertical or horizontal to indicate coupling between system scales at different levels or at the same level of hierarchy. It may also include the coupling between different facets of a system such as measures of socio-economic or socio-ecological activity. Applying SD-DES hybrid simulations, Chahal and Eldabi (2008) describe their design concepts for modelling healthcare governance in the UK's National Health Service. They emphasise the importance of understanding intra-departmental as well as inter-departmental interactions. In essence they propose the use of an SD-DES hybrid design to capture both horizontal and vertical integration issues within this system where different elements of the organisation are represented in either SD or DES modules.

Lane and Husemann (2008), in exploring positive feedback, discuss the relationship between social structures, norms and individual behaviours. They illustrate this decomposed feedback process which is simplified here for reference but which illustrates the concept of cross-scale coupling.

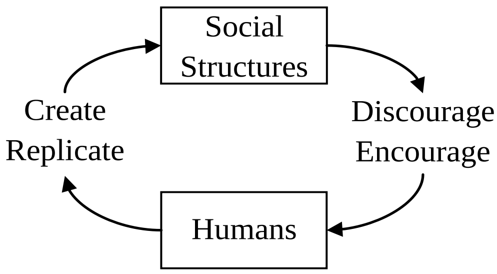


Figure 4-1: Interplay between acts of human behaviour and social structures, Lane and Husemann (2008, p. 55) (reproduced with permission: John Wiley and Sons RightsLink® licence – 3263680238163)

Mingers and Brocklesby (1997) also represent cross-scale coupling in their review of multi-method approaches to modelling and simulation presenting a framework that considers social, personal and material views of systems. Figure 4-1 shows the coupling of two of these as defined by Lane and Husemann (2008).

Parunak, Savit and Riolo (1998, p. 15) conclude that: “our ability to adopt the best modelling approach for a given problem depends on developing a collection of cases that demonstrate the respective strengths and weaknesses of the two [ABS and SD] approaches.” They look to reconstruct their ABS model representation of a supply chain with an SD representation. In describing the relative merits of each with regard to practical considerations for model structure, they observe that, “AB models are better suited to domains where the natural unit of decomposition is the individual rather than the observable or the equation.” They reinforce this by going on to state that, “equation based models may be better suited to domains where the natural unit of decomposition is the observable or equation rather than the individual.” As their observations form the basis for decomposing models in this thesis, it is important to recognise that they are reinforced by others working in different application domains:

- Comparing SD, based on difference equations, with ABS modelling for the spread of disease, Rahmandad (2004) concludes that ABS modelling can better capture the impact of local network structures on the diffusion process. Such local structures can be responsible for non-diffusion, which might not be predicted by more aggregate level modelling such as SD.

- Wakeland, et al. (2004) reported on their investigation into the use of SD and ABS modelling for cellular receptor dynamics and their comparative potential for use in education or for planning experiments. While they did not find a simple dividing line indicating when one paradigm or the other would be clearly preferred. They did note that these techniques were complementary, observing that SD is a more natural choice for highly aggregated modelling, while ABS is better suited to studying phenomena at the level of individuals. They also concluded that SD models represent the relationships between variables very effectively while AB models force more careful consideration of the definition of agents and the specification of their behavioural rules. AB models are better suited to spatial representation and are able to easily portray interactions at the cellular/molecular level.
- Alvarez, et al. (2006) describe the need to capture social tensions within their SD model which represents the broader system aspects arising from the development of the Panama Canal. While they propose to explore neural networks for this purpose, the need to look elsewhere to enhance representation of this social dynamic is noteworthy.
- Demirel (2006) reports on an experiment to replicate modelling of a Supply Chain in SD or ABS (using STELLA® and NetLogo respectively – see Annex A). A key observation recognises the heterogeneity of agents with respect to their choices and behaviour.
- Marin, et al. (2006) report on their SD model for workforce planning within NASA's Kennedy Space Centre. Echoing the observations of Shanthikumar and Sargent (1983), regarding the preference of analytic models to simulation models on the basis

of cost and computational efficiency (discussed further in Chapter 5), they chose to develop their model using SD as they perceived that the complexity associated with other methodologies would be prohibitive. However, in order to enhance the representation of decision-making in their model and especially ‘lower-level’ decision-making, they proposed to incorporate an ABS model.

- Lorenz and Jost (2006) explore factors in choosing modelling paradigms to appropriately represent and analyse complex systems and sub-systems. In working towards an ‘orientation framework’ in which the purpose, method and object of modelling a system are factored into model selection, their general findings align to the higher level concepts defined by Parunak, Savit and Riolo. However, they also include the need to consider spatial and heterogeneity factors (that can be considered within ‘local conditions’) proposing three types of environment for ABS. The findings of Lorenz and Jost are combined with those of Parunak, Savit and Riolo later in this chapter.

In presenting a review of simulation modelling tools and techniques, Borshchev and Filippov (2004) indicate the relationship between level of abstraction and the appropriate application of modelling paradigms. However, as highlighted earlier, abstraction in terms of coupled scales of a system has a relative as well as an absolute meaning. For example, ABS is good at representing the decision-making of individuals, but may also be used to represent the decision-making of individual companies or indeed of individual nations (Swinerd, 2012). Consequently, the level of abstraction has to be placed within a context of system hierarchy when considering hybrid model design, as illustrated in Figure 4-2. Here, two example constructs for hybrid simulation models are represented comprising two or three modules. The two-module design incorporates an SD module to represent aspects of the system at higher levels of scale than in the ABS module. For the three-module design example, separate

ABS modules would represent both the highest and lowest layers of system scale, while an SD module would represent the intermediate layer.

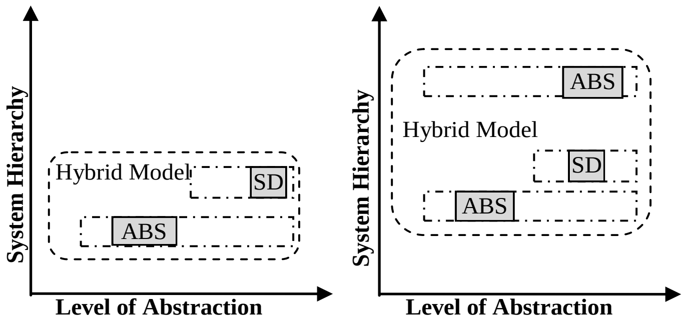


Figure 4-2: Levels of abstraction and system hierarchy within hybrid simulation constructs

Before moving on to consider a framework for capturing and representing the content of conceptual models, this brief analysis has highlighted the concept of system hierarchy and scale. This is important as one potential benefit of hybrid AB-SD simulation modelling may prove to be the potential to readily incorporate and analyse coupling across system hierarchy.

4.2 Capturing the Content of a Conceptual Model in a General Framework

Here, the works of Parunak, Savit and Riolo (1998) and of Lorenz and Jost (2006) are combined. These works are used as they both provide fundamental insights into the structure of simulation modelling rather than focussing at the physical layer such as with Gröβler, Stotz and Schieritz (2003) and Lättilä, Hilletofth and Lin (2010). Looking to provide general guidance, it is important that the underlying constructs used to represent the design transition are abstract and not tied, or limited, by specific scenarios or methods. Having defined the underlying structure and represented it in a general framework, it is then tested against a wide range of studies in order to demonstrate general application.

In their review of ABS versus equation-based modelling, Parunak, Savit and Riolo (1998) describe critical relationships that differentiate these approaches, identifying them as unifying multiplicities:

- "*Individuals are characterized, separately or in aggregate, by observables, and affect the values of these observables by their actions.*"
- *"Observables are related to one another by equations."*
- *"Individuals interact with one another through their behaviors*." [sic]

(Parunak, Savit and Riolo, 1998, p. 10)

Whilst observables might embrace the environment in which individuals are operating, it is proposed here that the environment and the interactions of individuals and observables with the environment must be explicitly captured also. In terms of AB modelling especially, the interaction of agents with their environment is a consistent factor when this paradigm is introduced as part of a training course or simulation study, e.g. Macal and North (2006, 2010) and Brailsford (2012), or in conceptual modelling (Onggo and Karpat, 2011). In SD and ABS modelling, the context in which the model is used is always described, even if as an academic case study to explore simulation modelling itself rather than some real world application. It is proposed, therefore, that the unifying multiplicities defined by Parunak, Savit and Riolo should be grounded in the environment of the system being modelled. As previously represented in Figure 2-1, the conceptual model is framed by both the real-world problem being addressed and the specific decision being supported through simulation.

Lorenz and Jost (2006) introduce an orientation-framework for multi-paradigm modelling with the aim of aligning purpose, object and methodology. As part of this work, they explore the concept of 'alternative environments' in agent-based modelling: a 'zero' environment with which agents do not interact but which may contain some aggregate parameters for use in an agent model; a 'passive' environment that does not contain any inherent dynamics but with which agents can interact with variables or structures; and finally an 'active' environment which is dynamic and an active part of the agent model. They note that an SD model could be used to build the 'active' environment.

It is proposed here that combining the unified multiplicities of Parunak, Savit and Riolo (1998), with the alternative environments described by Lorenz and Jost (2006), establishes a general decomposition that could be used to consistently capture the content of conceptual models as illustrated in Figure 4-3. Inclusion of the environment in this way also provides the opportunity to represent the context of the study and, hence, make apparent some, if not all, objectives of the conceptual model.

The general framework, therefore, comprises three basic element types (individuals, observables and the environment) and defined interfaces between them. The interfaces between individuals and observables are entirely consistent with that defined by Parunak, Savit and Riolo (1998). The environment element has been integrated into the framework using a ‘reports’ interface to the other elements. There is no interface defined to other environments as only one representation of environment is required; any need to represent another environment would be satisfied by use of another, separate, model. A reporting relationship is defined for interfaces with the environment element as this is consistent with Lorenz and Jost’s description of their alternative environments. The looped behaviours and equations interfaces to individuals and observables, respectively, allow for multiple instances of these elements as will be discussed later in the chapter.

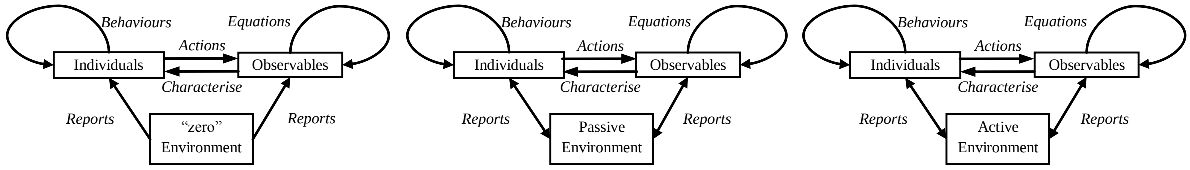


Figure 4-3: General framework for capturing the content of conceptual models for hybrid AB-SD simulations (unifying multiplicities reproduced with permission: Springer RightsLink® licence – 3227560368337)

The interfaces between elements are important as they define at a high level the direction of data or information flow. As detailed in the software engineering standards for the European Space Agency (Mazza, et al., 1994, p. 31), data structures between software components (elements here) should be defined in the Architectural Design Document covering:

- Description (e.g. name, type, dimension);
- Relationships (e.g. the structure);
- Range of possible values; and
- Initial values.

This structure is readily incorporated in the general framework, as presented in a case study later in this chapter. In doing so, it bounds the design to which detailed model specification and implementation must comply (Macal and North, 2006, p. 78-81; Rioux and Lizotte, 2011; Guizzardi and Wagner, 2012).

Having defined a general framework, the next stage was to conduct a review of the literature in order to determine whether the content of conceptual models could be identified and, if so, represented within this framework.

4.3 A Review of the Content of Reported Conceptual Models

Drawing from a diverse range of application areas (from workforce planning to public health and social care provision and from the international diffusion of technological innovation to land management science, for example), a review of reported hybrid models was conducted.

The literature reviewed covered the timeframe 1999 to 2013, representing the initial period of growth in the reported use of hybrid models (Table 1-1).

In order to facilitate a comprehensive and consistent survey, a tabulated form was designed that captured both Robinson's definition of a conceptual model (as defined in Chapter 2) and the implementation of the reported model. The form, Table 4-1, also prompts for an assessment of alternative modelling strategies. As part of the assessment of model implementation, the three design classes introduced in sub-section 2.5.3 are also included. These design classes (Swinerd and McNaught, 2012a) are described in Chapter 5.

Table 4-1: Form for reviewing the reported content of conceptual models and model implementation plus assessment of alternative options for implementation

<table>
<tr><td>Author(s) and Reference(s)</td><td colspan="2"></td></tr>
<tr><td>Real World Problem</td><td colspan="2"></td></tr>
<tr><td>Modelling Objectives</td><td colspan="2"></td></tr>
<tr><td>Inputs (Experimental Factors)</td><td colspan="2"></td></tr>
<tr><td>Outputs</td><td colspan="2"></td></tr>
<tr><td>Content</td><td colspan="2">Content of the conceptual model captured diagrammatically in the proposed general framework.</td></tr>
<tr><td>Assumptions</td><td colspan="2"></td></tr>
<tr><td>Simplifications</td><td colspan="2"></td></tr>
<tr><td>Design Schematic (not all reported outputs shown)</td><td>Implementation</td><td>Alternative Options</td></tr>
<tr><td rowspan="4">Schematic diagram of model as reported.</td><td rowspan="2">Design Class:
Interfaced/Sequential/Integrated</td><td>Sequential/Integrated/Interfaced:</td></tr>
<tr><td>Integrated/Interfaced/Sequential:</td></tr>
<tr><td rowspan="2">Hybrid(ABS/SD/DES/CA)/AB/SD
[Modelling Tool(s) used]</td><td>ABS: as an option?</td></tr>
<tr><td>SD: as an option?</td></tr>
</table>

Without direct access to authors, the conceptual model was derived based on both explicit and inferred evidence drawn from that reported. Direct correspondence with authors and model designers would probably enhance the findings from this review and could be a topic for future work. Consequently, the full results of this review are provided at Annex C for reference.

The content of the conceptual model for each study reviewed was mapped to the proposed general framework. In each case a schematic representation of the actual design of the model was also captured. This outline process is summarised in Figure 4-4. The content of the conceptual model is extracted from a research article and recorded in the form. Whilst completing this review, a design schematic of the model as reported plus an assessment of alternative approaches for implementing the model are recorded. The content of the conceptual model is represented using the general framework, retaining the completed assessment form for future reference and cross-validation. The author has found that this process requires a few passes in order to refine the information captured securing what are often subtle comments on model design. Finally, the general framework for that model can be enhanced by representing detailed data structures for the interfaces between modules. This additional step can further refine the data capture process and was found to be a useful exercise during literature review. This process can take many hours per research article.

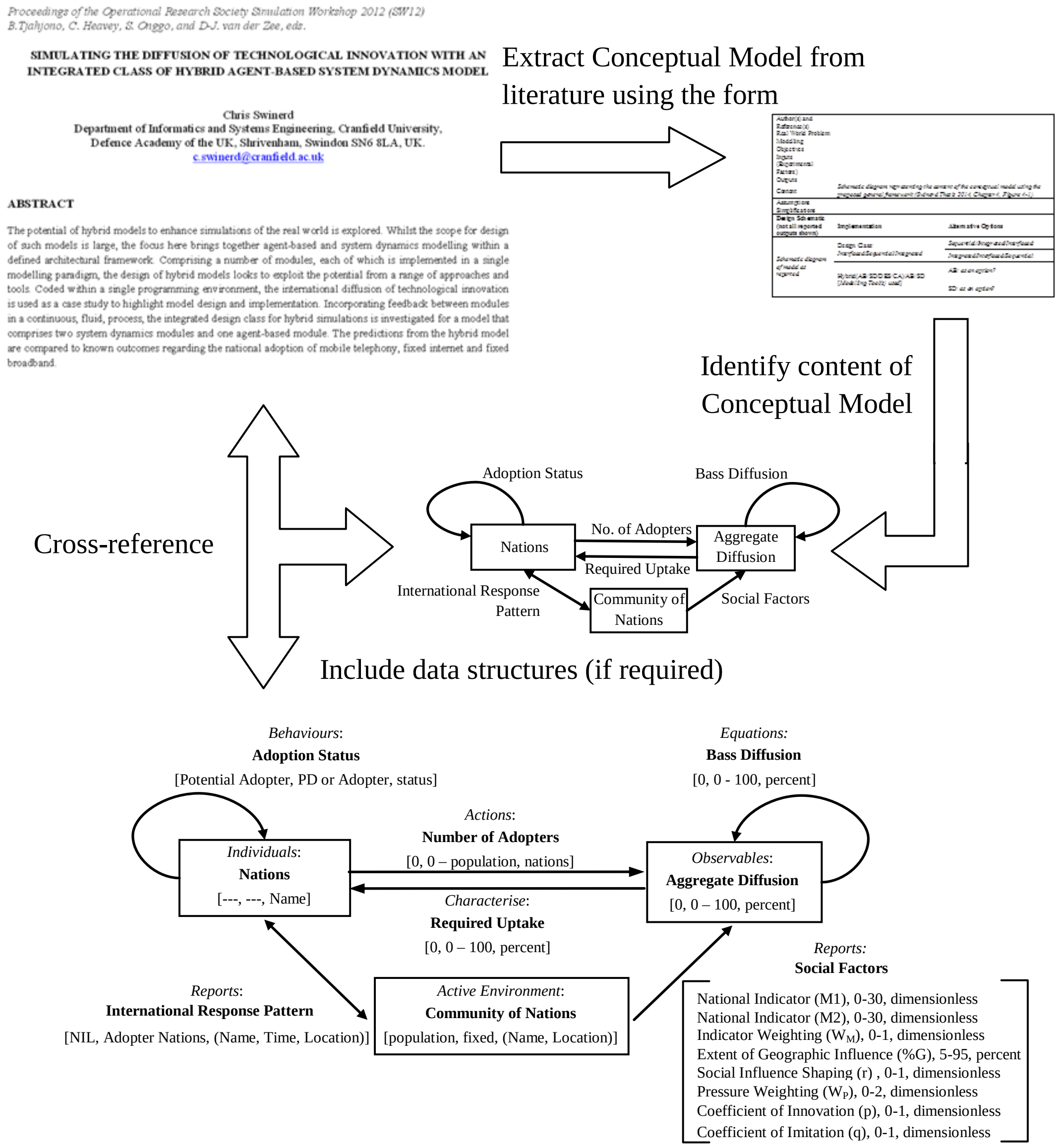


Figure 4-4: Process for defining the reported content of conceptual models

Complementing the case study of Sterman's (1985) model of path dependence, competition, and succession in the dynamics of scientific revolution presented in Annex B, the inferred content of Sterman's conceptual model is represented in Table 4-2. The aim of the case study at Annex B was to demonstrate that NetLogo could be used to construct a hybrid AB-SD design of Sterman's original agent-oriented SD model (Sterman, 1985). Here, his model is represented in the general framework including representation of detailed data structures.

Table 4-2: (Case Study) Representing Sterman's model of path dependence, competition, and succession in the dynamics of scientific revolution through the general framework

Sterman (1985), and later Sterman and Wittenberg (1999), present a model of path dependence, competition and succession in the dynamics of scientific revolution. The inferred content of their conceptual model is presented at Figure 4-5 against which the following outline summary of the model refers. The focal point of their model is confidence. As puzzles in a scientific paradigm are solved so confidence in it grows attracting more resources and practitioners. However, the general level of difficulty associated with puzzles grows as the number solved increases relative to the intrinsic capability of that paradigm. With increasing difficulty, some puzzles remain unsolved for long enough to be recognised as anomalies. Resources are then diverted away from puzzle solving to anomaly resolution. Whilst some anomalies are solved, some persist raising doubt over the science in that paradigm, and hence reducing confidence in it. Relative to other paradigms, the level of confidence associated with a paradigm determines recruitment and defection rates. Depending upon the balance of resource allocation between puzzle solving, anomaly resolution and other activities in the dominant paradigm, new science paradigms are created with a defined probability. Those with a complete loss of confidence cease to exist. This model, therefore, represents the path dependence of the rise and fall of scientific paradigms over time.

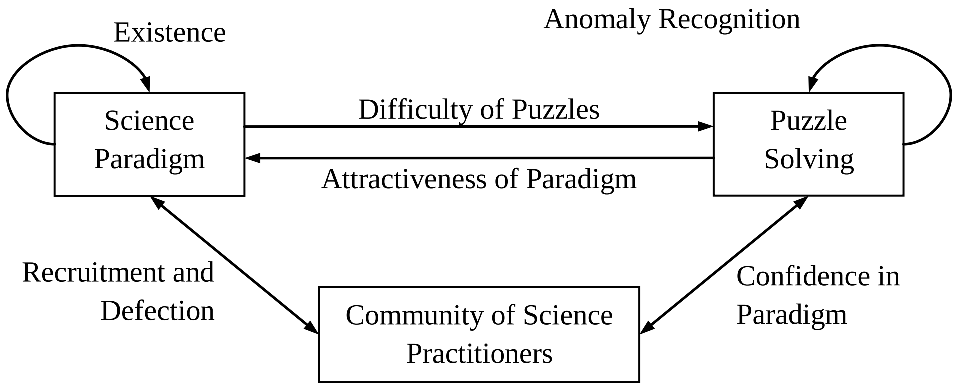


Figure 4-5: General framework representation of the content of the inferred conceptual model for Sterman's model of scientific revolution

The general framework as presented in Figure 4-5 arguably captures the content of Sterman's model in a concise and clear format. The key elements of the conceptual model and the interfaces between them are defined; hence, it is possible to use this to inform options for the implementation, verification and validation of the model. By defining more accurately the data and information types in the framework however, it is possible to enhance the audit trail from conceptual model to model specification without overly complicating presentation. With the arrowheads representing the direction of data or information flow, this representation is modified so that the data or information types presented are described in accordance with the software engineering guidelines introduced previously in the chapter:

Type: **Name** [initial value, range of values, units].

The enhanced representation is provided in Figure 4-6.

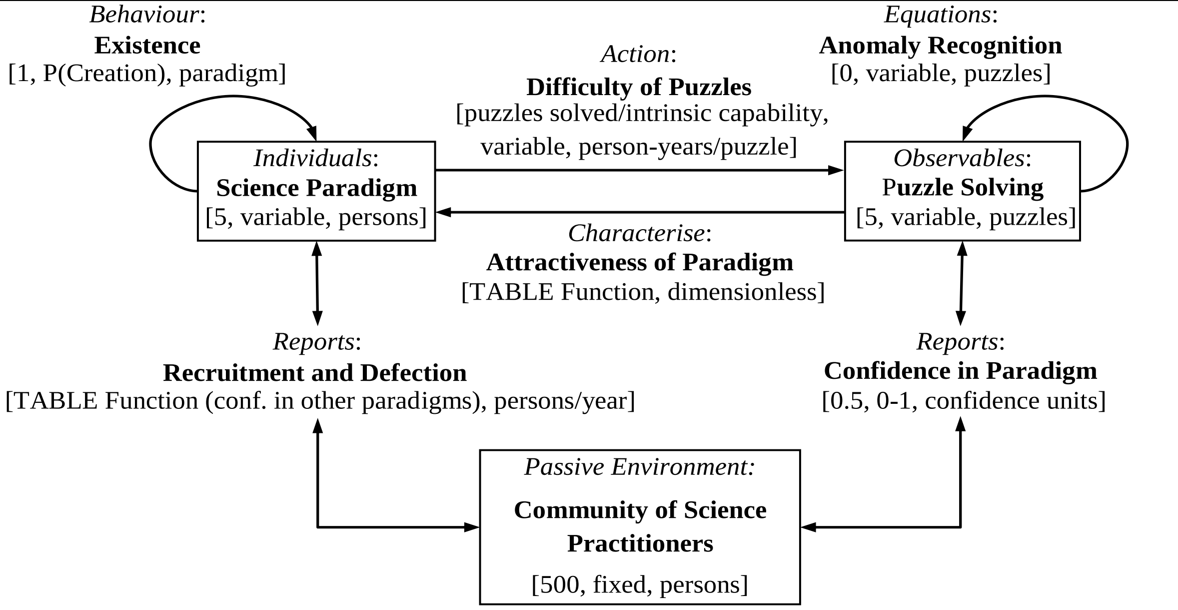


Figure 4-6: Enhanced general framework representation of Sterman's model of scientific revolution

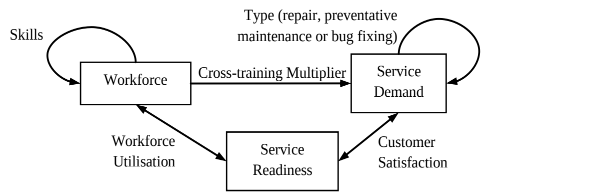
By using the defined format to represent data and information types, it is clear that further information is made available without significantly compromising the clarity of model representation. The author has also found that using this structure forces greater consideration when representing the content of the conceptual model in this way.

With the community of science practitioners fixed at 500, the environment is classified as passive according to that described by Lorenz and Jost (2006). Being an agent-oriented SD model, the behaviour of individuals required careful consideration. The dominant behaviour of paradigms, however, is whether they exist or not. Whilst active, they take resource, represent competition to other paradigms and contribute to the conditions for potential creation of new paradigms. The general units for data and information are now defined primarily consisting persons, puzzles, confidence units and years. Non-linear relationships are defined based, in this case, on table functions. As represented in Figure 4-4, it is possible that data types can comprise arrays or other complex data structures. In this modular presentation format, opportunities for verification can also be assessed as discussed in sub-section 4.5.

Across 18 diverse simulation studies listed in chronological order, the principal results from this analysis are summarised at Table 4-3. In respect to the design schematics, boxes are used to represent single paradigm modules, ovals represent named output from the model (not all outputs are represented in all cases), and curved boxes represent a non-paradigm contribution such as bespoke computer generated data or some other data source; arrowheads represent the direction of data or information flow. For now, the general framework is restricted to a single representation of individuals, observables and environment, although this restriction is relaxed later in the chapter.

Table 4-3: The content of 18 conceptual models represented within the proposed general framework and schematic diagrams of the actual implementation of each model

<table>
<tr><th>Authors</th><th>Conceptual Model Content</th><th>Design Schematic</th></tr>
<tr><td>Homer

(1999)</td><td>


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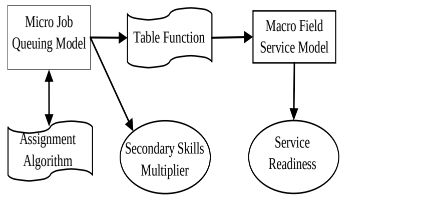
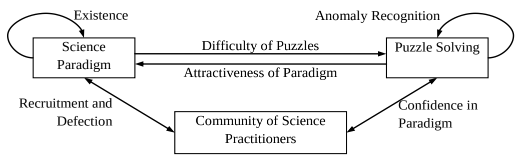


</td></tr>
<tr><td>Steman

and

Wittenberg

(1999)</td><td>


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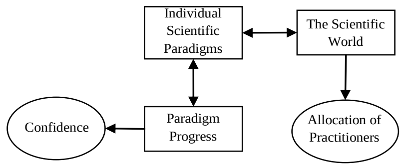
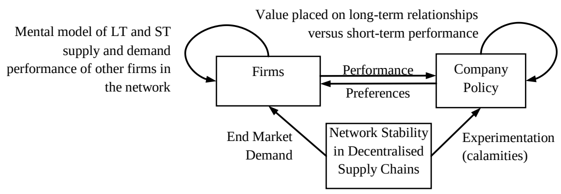


</td></tr>
<tr><td>Akkermans

(2001)</td><td>


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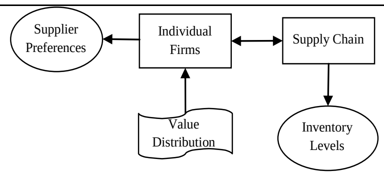
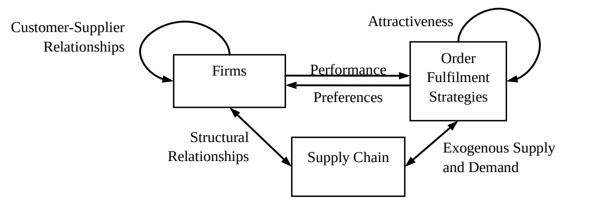
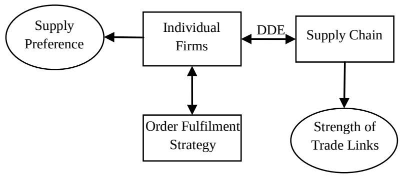
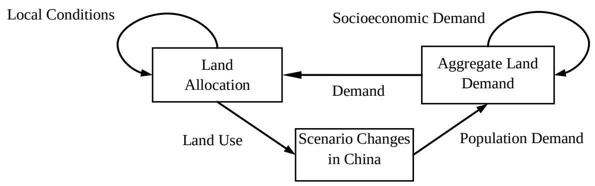
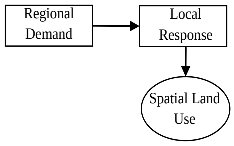
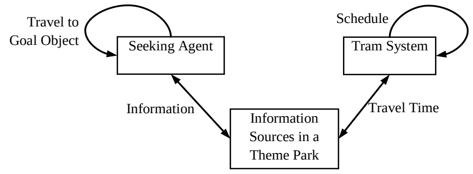
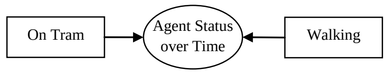
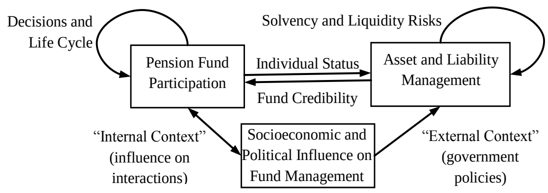
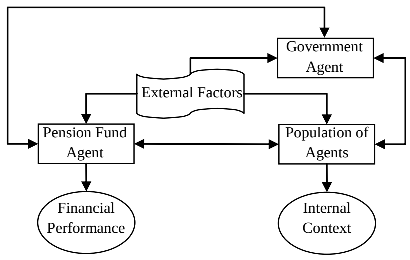
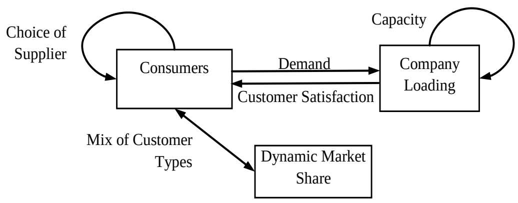
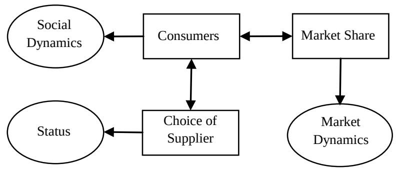
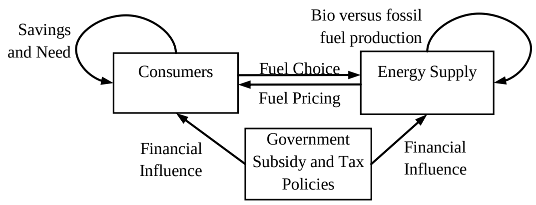
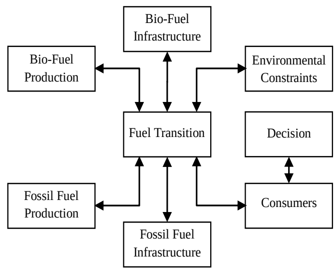
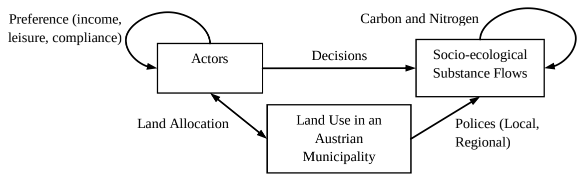
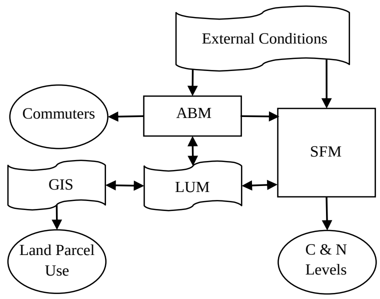


</td></tr>
</table>

Schieritz and Gröβler (2003)		
He, et al. (2004)		
Dubiel and Tsimhoni (2005)		
Chaim and Streit (2008)		
Duggan (2007)		
Meza and Dijkema (2008)		

<table>
<tr><td>Gaube, et al. (2009)</td><td>
</td><td>
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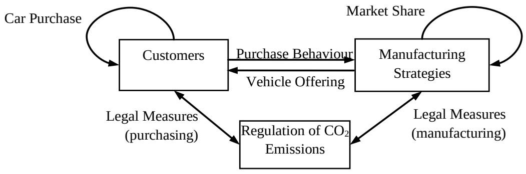
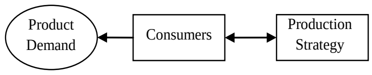
<tr><td>Kieckhäfer, et al. (2009)</td><td>
</td><td>
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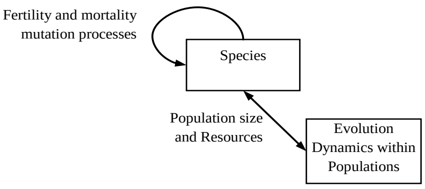
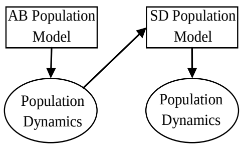
<tr><td>Schieritz and Milling (2009)</td><td>
</td><td>
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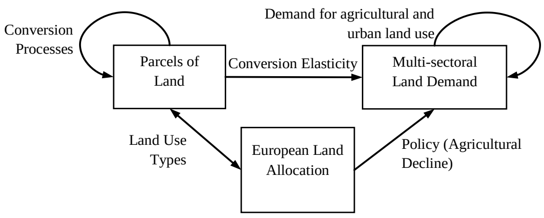
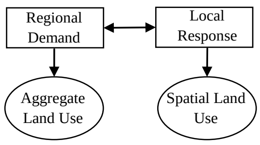
<tr><td>Verburg and Overmars (2009)</td><td>
</td><td>
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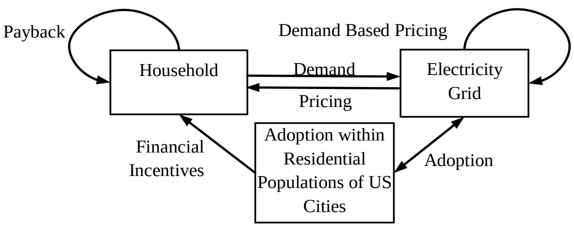
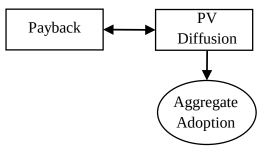
<tr><td>Zhao, et al. (2011)</td><td>
</td><td>
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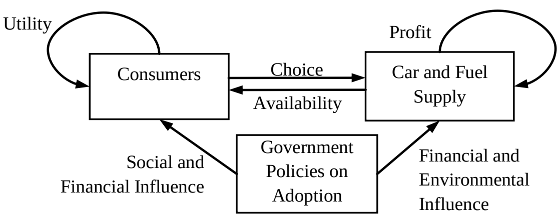
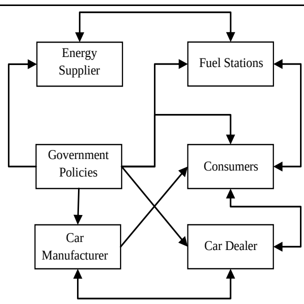
<tr><td>Shafiei, et al. (2012) [Whilst potential outputs discussed, none shown hence none shown here]</td><td>
</td><td>
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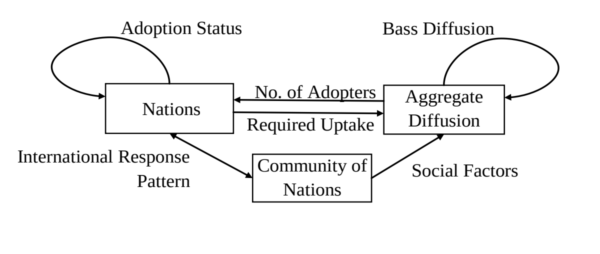
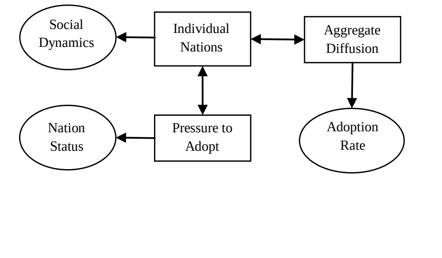
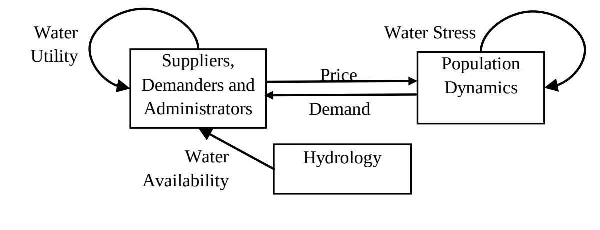
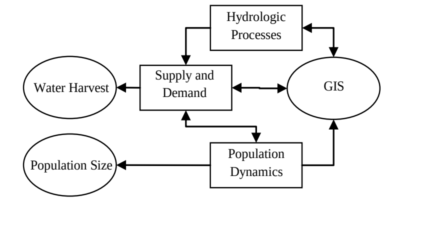
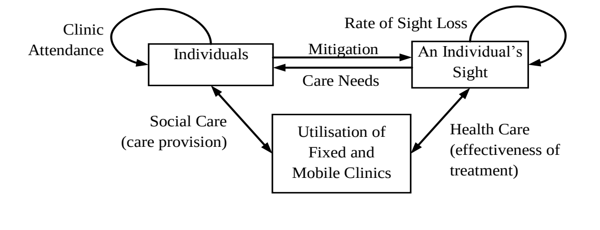
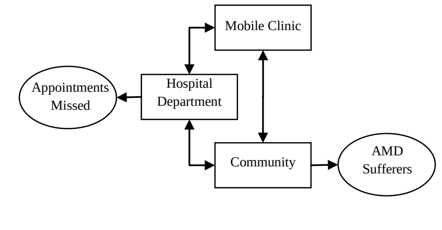
Swinerd and McNaught (2012a)		
Nikolic, et al. (2013)		
Viana, et al. (2012)		

Based on these results some general observations can be made. Firstly, individuals should be considered in the widest sense as uniquely identifiable with defined behaviours relevant to the system problem being modelled. Given the explicit inclusion of the environment in the framework, and hence system context, a detailed representation of individual behaviour may not, however, be required. Simon (1996, p.62) hypothesises:

"*that in large part human goal-directed behaviour simply reflects the shape of the environment in which it takes place; only a gross knowledge of characteristics of the human information-processing system is needed to predict it*."

Beyond individual people, individuals might include any living being, a team, organisation or nation for example.

Secondly, all four possible types of interface between individuals and observables have been identified as illustrated in Figure 4-7.

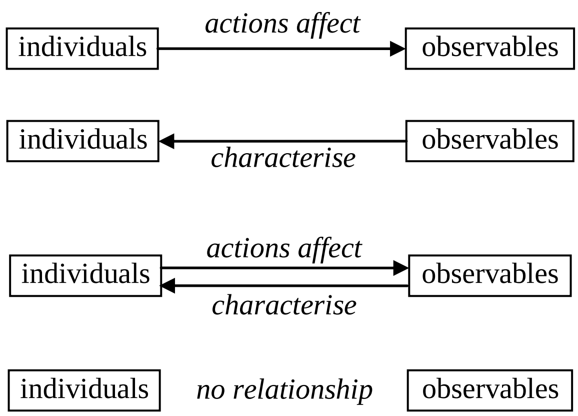


Figure 4-7: Interfaces between 'individuals' and 'observables'

Thirdly, the interface between individuals or observables and the environment also differs depending upon the context of the simulation study. Examples of both unidirectional and bidirectional relationships have been identified in the 18 studies reviewed. Consistent with the general description of AB modelling and as demonstrated in this review, individuals must always have an explicit interface with the environment. It is possible, however, for no interface to exist between observables and the environment. It is also possible that the population of individuals can be the environment. The allowable interfaces between the environment and individuals or observables are shown in Figure 4-8.

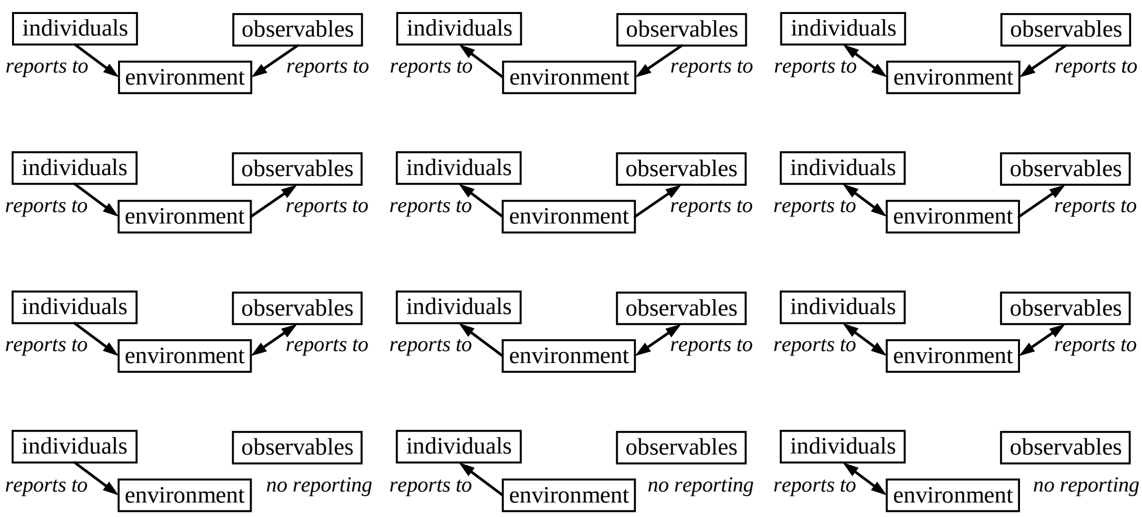


Figure 4-8: Possible interfaces between the 'environment' and 'individuals' or 'observables'

Whilst the detail of model implementation is clearly unique to each study, it has been possible to map the content of the inferred conceptual model to the general framework in each case. Whether the authors of the reported studies would agree is, of course, a matter for conjecture. It is interesting to note, however, that Kieckhäfer, et al. (2009, p. 1434) explicitly represent their model in a manner entirely consistent with the proposed general framework, which suggests merit in this approach. Assuming that each model is appropriately represented, the framework has provided a consistent approach to directly compare the underlying design choices of a wide range of hybrid models. The combined potential of defined interfaces for the general framework provide up to 48 unique combinations (the twelve combinations in Figure 4-8 for each of the four combinations in Figure 4-7). As described in the treatment of software engineering standards by the European Space Agency (Mazza, et al., 1994, p. 30), "there is no unique design for any software system". The range of combinations available within the general framework supports this realisation and, consequently, allows the early design plans for a model to be explored and provide an audit trail from conceptual model to model specification.

It is possible that either individuals or observables are not part of the conceptual model as highlighted in Figure 4-9. In such cases, a hybrid modelling approach may not be appropriate. The general modelling framework represents, therefore, the spectrum of modelling options for ABS and SD from single paradigm modelling to hybrid modelling. This spectrum is mapped to the general framework in Figure 4-9 where dashed interface lines can be adjusted to be unidirectional, bidirectional or not present in accordance with that defined in Figures 4-7 and 4-8. This representation against the spectrum of modelling options potentially highlights the scope of utility for hybrid models, which is discussed in detail in Chapter 6.

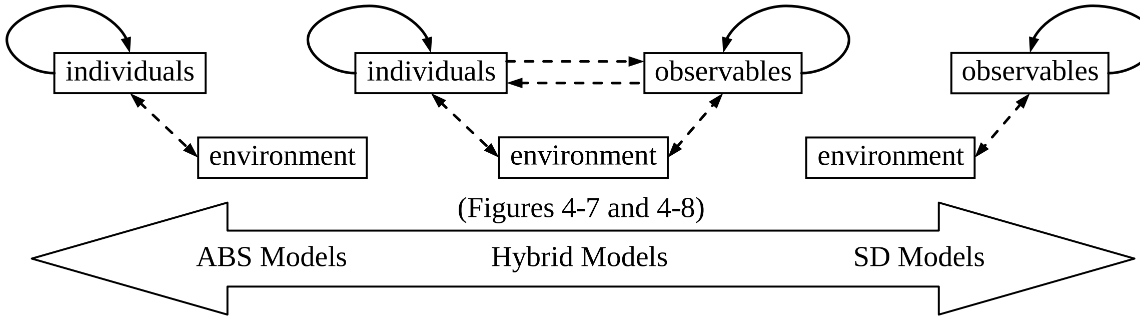


Figure 4-9: General Framework mapped to the AB-SD spectrum of modelling

At this stage the output of the model has not been represented with the general framework, although there is often a close link to the description of the environment. The output of the model is included within the architectural design as discussed in Chapter 5. A general framework with apparently isolated observables element(s) will be integrated in the model architecture through contribution to model output.

4.4 Multiple Instances of Individuals or Observables

Throughout the analysis presented in this chapter, the general framework has been limited to a single representation of elements representing individuals and observables. This limit was self-imposed in order to focus on the general trends revealed by comparing a diverse range of studies; this limit may not, however, be necessary. Within the literature reviewed, there are instances where multiple representations of individuals, e.g. Shafiei, et al. (2012) or Chaim and Streit (2008), could be included or of observables, e.g. Shafiei, et al. (2012) or Swinerd (2012). Given the opportunity to explore both options, the work of Shafiei, et al. (2012) is used here to demonstrate the inclusion of multiple elements and to illustrate the role of the general framework in informing design choice.

The design schematic representing the model implementation by Shafiei, et al. in Table 4-3 is a close representation of their diagram of "interlinked modules for diffusion of AFVs (Alternative Fuel Vehicles)" (Shafiei, et al., 2012, p. 1075). As presented in Figure 4-10, they indicate modelling implementation for each module suggesting either an ABS or SD approach. For their 'fuel stations' module, however, they indicate that either an ABS or SD implementation could be used. Here, the implication of this single modelling choice is represented through the general framework incorporating multiple instances of individuals and observables.

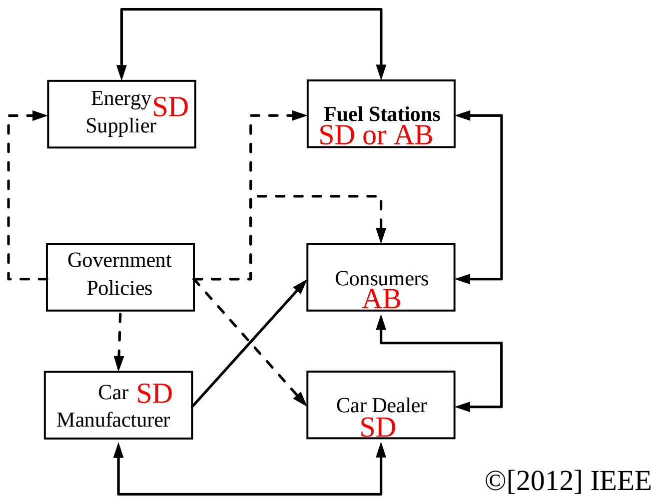


Figure 4-10: Schematic representation of the hybrid AB-SD model by Shafiei, et al., (2012)

The impact of either choice on overall design of the model and on interfaces between modules in particular, is clearly illustrated in Figure 4-11: a simplified mapping of ABS and SD modelling paradigms, respectively, to individuals and observable elements of the framework is assumed. As demonstrated through the review of agent-oriented SD models, this mapping may not be universally correct but it is sufficient for this analysis. In order to provide clarity, the 'reports' interfaces with the environment element are shown as dashed lines with no label included.

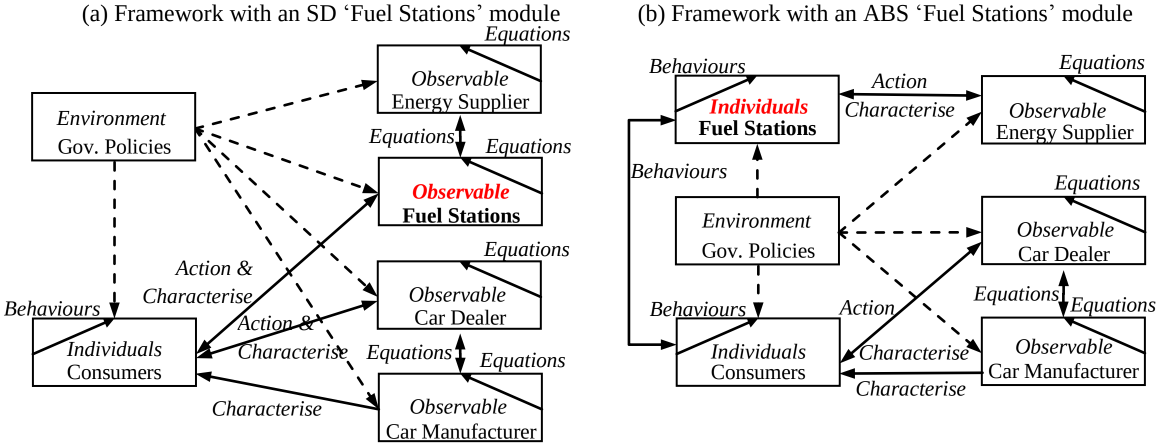


Figure 4-11: Representing the implications of module implementation with multiple instances of individuals and observables in the general framework with either SD (a) or ABS (b) chosen to implement the 'Fuel Stations' module

With the 'fuel stations' module implemented in SD (Figure 4-11(a)), the interface to the 'consumers' module is established through 'action' and 'characterise' relationships. Both being observables, the interface to the 'energy supplier' module is based on equations. If the choice, however, is to implement the module using ABS (Figure 4-11(b)), so these interfaces change. The interface to 'consumers' must now be based on behavioural relationships whilst the interface to 'energy supplier' must be based on 'action' and 'characterise' relationships.

The implication of this choice is clear and will shape the task of verification and validation. The inclusion of multiple instances of individual and observable elements in the general framework has not hindered the presentation of proposed model designs. Providing the interface relationships are correctly represented, the use of multiple elements within the general framework is an option should it be required.

4.5 Verification and Validation

Sargent (2013) considers a range of techniques available for conducting verification depending on whether the simulation model is to be implemented in a high-level programming or a bespoke simulation language. As part of this review, he considers “computerized model verification” [sic] (Sargent, 2013, p. 14) which incorporates specification verification (see Figure 2-6) and is of primary concern to the design transition.

For a high-level programming language such as FORTRAN, C or C++, for example, then Sargent (2013) lists object-oriented design, structured programming and program modularity as options. If bespoke simulation languages are used, he describes the confirmation of error-free languages, proper implementation, correct random number generation and programming correctness. He also discusses techniques for conducting static and dynamic testing (Sargent, 2013, p. 18) citing the work of Fairley (1976). Options for static testing include; structured walkthrough, correctness proofs, and examining the structured properties of the program. For dynamic testing, he highlights the use of traces, input-output investigations, data relationship correctness and the reprogramming of critical components to see if model output is affected.

It is proposed that the adoption of the general framework to represent the content of the conceptual model supports a number of the options identified by Sargent for verification during the design transition. In particular, the use of structured programming, programme modularity, tests for proper implementation, data relationship correctness and the reprogramming of critical components of the programme would all be facilitated through the formal use of the general framework approach. As discussed when highlighting the need for guidance for the design transition (see sub-section 2.6), these benefits will be realised primarily through increased efficiency of the modelling process including the potential for code re-use. As Sargent (2013, p. 12) comments: “several versions of a model are usually developed prior to obtaining a satisfactory valid model.” In which case, code re-use aids efficiencies in both project time and cost, which may be facilitated by using the general framework for managing the content of the conceptual model and how it is coded.

4.6 Management of Units and Time

Further considerations for hybrid model design are consistency of units and appropriate representation of timing. Chahal, Eldabi and Mandal (2009) describe types of interactions between models within a hybrid design, in this case comprising SD and DES. They describe 'cyclic' interactions, where the models run separately and information is exchanged between consecutive runs with no interaction during run time; 'parallel' interactions, where the models are run at the same time and information is passed between them; and 'planetary' interactions where the DES model runs for every time-step of the SD model with data exchange taking place every time-step. The degree of correspondence between these interaction types and design classes to be introduced in Chapter 5 will be evaluated in Chapter 6. Examples of time management are also provided by Venkateswaran, Son and Jones (2004) in their SD-DES hybrid model for production planning. Alvanchi, Lee and AbouRizk (2009) consider the need to exchange information only when meaningful, i.e. when something has changed. They also recognise that this concept is a function of how different modelling paradigms represent time.

4.7 The Design Transition Revisited

The design transition was described in Chapter 2 where it was established that the content of the conceptual model mostly informs design choice during this transition and that the technical systems engineering processes of architectural design and integration mainly apply. Using the general framework introduced for Sterman's (1985) model of scientific revolution in the case study at Table 4-2, the relationships between the material presented in this chapter and the design transition is highlighted in Figure 4-12.

Through its elements, the general framework defines the key modules for the model and the interfaces between them. Whilst any number of 'individuals' or 'observables' elements can be used, only one 'environment' element is allowed. An initial outline assessment of the technical performance of the model is possible based on the framework, especially with the inclusion of formally defined data structures. The general framework also aids planning for specification verification supporting a number of options for verification as described by Sargent (2013). Further work is required, however, to address architectural description and integration. Whilst the general framework informs both, it does not go far enough to provide sufficient information on which to establish the basis for model specification or implementation. This is the subject of Chapter 5 where design classes for hybrid models are introduced.

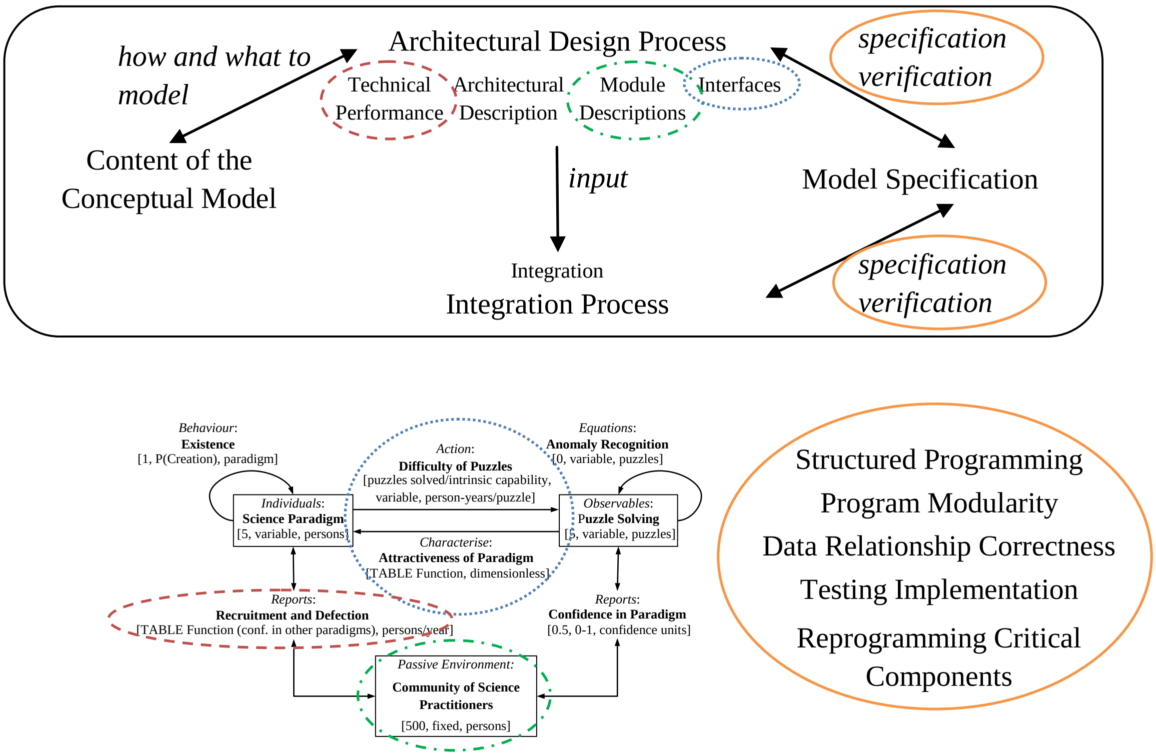


Figure 4-12: Mapping information provided through the general framework to the design transition

4.8 Chapter Summary

The focus for this chapter has been the definition of a consistent method for representing the content of conceptual models. Based on fundamental observations of model structure and drawing from standards in software engineering, this chapter has:

- Defined a general framework comprising key elements and interfaces with which to represent the content of the conceptual model.
- Successfully used this framework to consistently represent a diverse selection of reported models from which valid combinations of elements and interfaces have been described.
- Highlighted the potential to facilitate verification during the design transition, an important contribution to reducing translation error from conceptual modelling to model specification.

Chapter 5 DESIGN CLASSES

This chapter builds on work presented in Chapter 4 by completing the detailed analysis of the design transition. As highlighted in Figure 5-1, the focus of this chapter is architectural description and design integration.

Three design classes are defined and, encompassing a diverse range of application areas, examples of these highlighted in a review of the literature. Specific examples of design implementation within these classes are also discussed with illustrations used to reinforce design concepts.

Based on the reported reviews for this and the preceding chapter, the underlying factors for selecting a design class have been identified and are captured within a decision process.

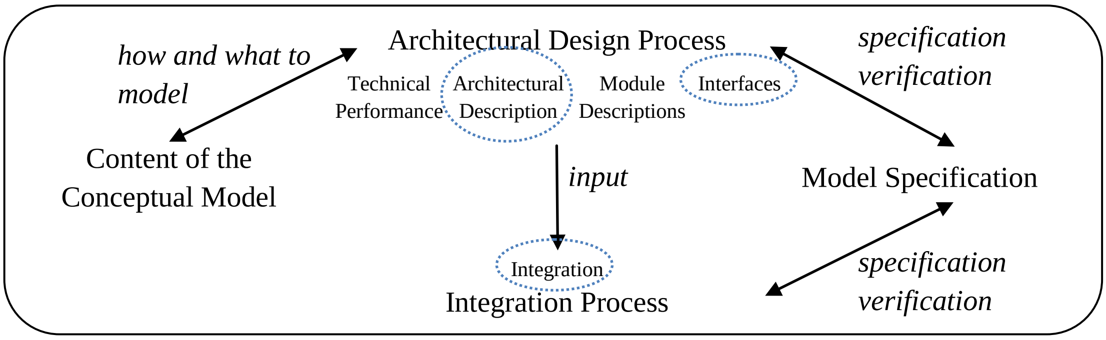


Figure 5-1: Elements of the design transition addressed in Chapter 5

5.1 A Unifying View

Focusing on hybridising simulation and analytic methods, Shanthikumar and Sargent (1983) and, in a later review, Sargent (1994), proposed a classification of hybrid models by outlining, with examples, four classes. They define analytic and simulation models as:

"*An analytic model is a set of equations that characterize a system or a problem entity. Its solution procedure usually uses either an analytical equation or a numerical algorithm that has been developed for the set of model equations to obtain the desired results. A simulation* *model is a dynamic or an operating model of a system or problem entity that 'mimics' the operating behavior of the system or problem entity and contains its functional relationships*." [sic] (Shanthikumar & Sargent, 1983, p. 1030)

Sargent, in his 1994 review, looked to assess the impact of his earlier work with Shanthikumar by comparing the work reported on hybrid modelling by the wider research community before and after its publication. He concluded that, despite significant advances in computer hardware and software systems, there was little evidence of real progress in adopting hybrid models (or modelling). He believed that, in the main, this was due to the lack of attention for this approach to analysis in textbooks or the classroom, where the various techniques tended to be considered in isolation. A further ten years later, Borshchev and Filippov (2004) confirm little change when they reflect on the ongoing segregation in the teaching of modelling techniques that can reinforce separate practitioner communities. Even today, one notes the tendency for most software packages (see Annex A), conferences, societies and journals to focus on specific paradigms of modelling and simulation.

Shanthikumar and Sargent (1983) observe that while simulation models permit a greater degree of realism than analytic models, the cost of model development and use is much cheaper for analytic models than simulation models. A key motivation for investigating hybrid design concepts, then, is to deliver cost-effective and computationally efficient solutions. Their original four classes of hybrid model are described as follows:

Class I – "*A model whose behavior over time is obtained by alternating between independent analytic and simulations models*." [sic]

Class II – "*A model in which a simulation model and an analytic model operate in parallel over time with interactions through their solution procedure*."

Class III – "*A model in which a simulation model operates in a subroutine way for an analytic model of the total system*." [sic]

Class IV – "*A model in which a simulation model is used as an overall model of the total system, and it requires values from the solution procedure of an analytic model representing a portion of the system for some or all of its input parameters*."

(Shanthikumar and Sargent, 1983, pp. 1034-1035)

They go on to propose that if the time-dependent behaviour of the system can be completely decomposed so that some part of it can be solved analytically then, on the basis of efficiency, one would choose a Class I hybrid model. If both model types are required to operate in parallel with respect to time and with interactions between them, then one would use a Class II hybrid model. Where complete decomposition is not possible, then again, on the basis of efficiency, one would prefer to use a Class III model rather than a Class IV model because the analytic model is, in general, cheaper and computationally more efficient. These model classes are reproduced in Figure 5-2.

Based on a review of published work covering a diverse range of application areas, it is proposed that for hybrid AB-SD simulation modelling, the four classes defined above (for combining simulation and analytic modelling) can be reduced to three and that these can be given meaningful, descriptive titles (for combining different simulation paradigms). Descriptive titles can be useful as they convey greater meaning and better infer the implementation of the hybrid design concept, which, in itself, may ease exploitation by students and practitioners of modelling.

In assessing the four classes defined by Shanthikumar and Sargent (1983), it can be seen that in the case of Class I, the output from analytic and simulation models are 'interfaced'. Here, it is proposed that the word ‘interface’ can be used to describe a point of interaction or communication between modules. When these modules are from different simulation paradigms, then the model is implemented using an interfaced hybrid simulation design.

Where it is possible to decompose subsystems, system hierarchy or scale (see sub-section 4-1), through appropriate and efficient use of modelling techniques but where the techniques need to be run in parallel and potentially include feedback between them, as with Class II, it is suggested that this design involves more integration between modules than the other classes. The word ‘integrate’ can be used to describe the combining or adding of parts to make a unified whole. It is unclear as to why Shanthikumar and Sargent (1983) used dotted lines to represent feedback between models within Class II as without this feedback the model approaches Class I. It is assumed that at least one of these feedback paths has to exist. The inclusion of feedback reinforces the concept of an integrated design. An integrated hybrid simulation is, therefore, defined as one which contains sustained feedback (not just at one point in time) between modules from different paradigms.

Finally, what Shantikumar and Sargent (1983) define as Classes III and IV both represent ‘sequential’ designs, whichever way around one type of model is used to inform the other. The word ‘sequence’ can be used to describe a logical order of events or processes. The use of one module strictly before the use of another defines a sequential hybrid simulation. The first simulation must be capable of producing the required input for the second simulation and then terminating before the second simulation begins. The output of the first simulation alone does not represent the output of the model.

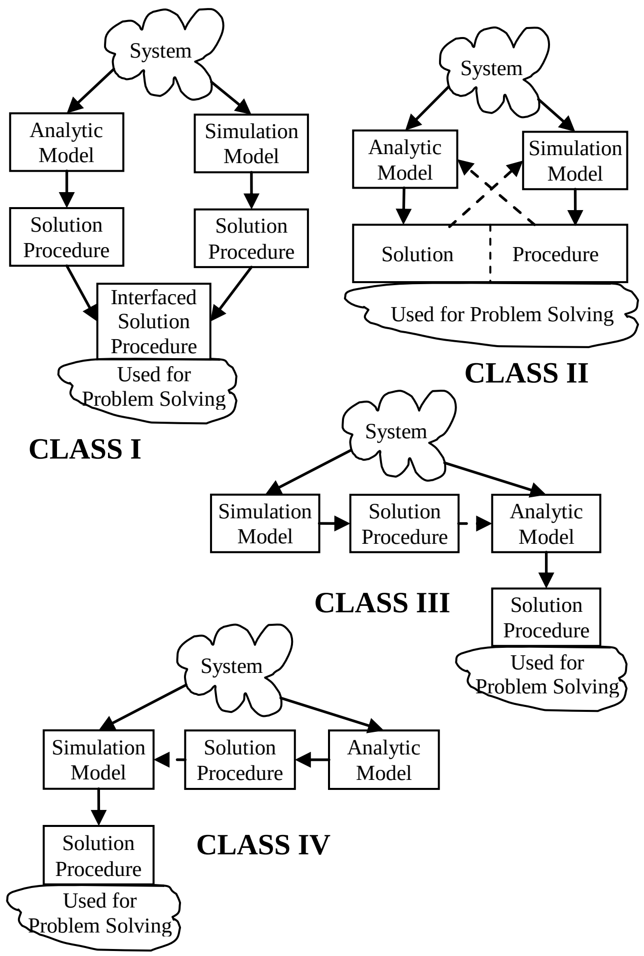


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Figure 5-2: Shanthikumar and Sargent's four classes of hybrid model

In reporting on their hybrid AB-SD model applied to Financial Stability, Martinez-Moyano, et al. (2007) describe three types of interaction between modules: 'scenario exploration', where the domain ABS model is run first and results are sent to the SD model (aligning to the sequential (Classes III or IV) design); 'intertwined models', where the domain ABS and SD models alternate and potentially pass information between them (aligning to an integrated (Class II) design); and 'crisis response', where the domain ABS model is run first on empirical input data and results are then passed on to the SD model (again aligning to the sequential (Class III or IV) design). They note that the division of labour between domain

ABS models and SD models is a major design decision. This recognises potential efficiencies in a simulation project associated with choices in the design transition. The recommendation of Shantikumar and Sargent (1983) for preferentially selecting a Class III design over a Class IV design on the basis of efficiency supports this view.

As previously introduced in sub-section 2.5.2, Lättilä, Hilletofth and Lin (2010) consider different methods to combine ABS and SD modelling paradigms; proposing five. Whilst this analysis does not consider fundamental design, they conclude that there is a continuum where, at one end, ABS models can be constructed with SD methodology used within agents, whilst, at the other end, ABS principles are used as part of a larger SD model. They also recognise the use of different modelling paradigms to model the same problem in order to assess reasons for complex system behaviour and also to complete sensitivity analysis.

As will be discussed later in this chapter, their reference to the use of SD within agents has been reported a number of times and is referred to here as 'agents with rich internal structure'. The uses of ABS design principles to inform SD model designs has been discussed in Chapter 2, sub-section 2.5.1, and is referred to as agent-oriented SD modelling. Whether this approach constitutes a hybrid AB-SD model classification is questionable, however, as it does not include modules implemented in more than one modelling paradigm. The use of one modelling paradigm to triangulate results, including for sensitivity analysis (noting potential computation load when using ABS for this purpose (Kortelainen and Lättilä, 2009, p. 18)), is a useful approach, but, again, is not considered here a hybrid classification when the output from either single paradigm model can be considered the output for the 'model'. Where the outputs from each single paradigm model, i.e. each module, are combined to provide in some way the model output, then this is an interfaced design. Their conclusion with respect to different model designs illustrating different complex behaviour is an interesting observation which aligns with the view of Holland (1999 cited in Scholl 2001b, p. 14) who discusses separating the ‘incidental from the essential’: as introduced in sub-section 2.5.2; i.e. results that truly represent behaviours of the system being modelled versus those that are shaped by the design and implementation of the model.

In contrast to the three design classes proposed here, Chahal, Eldabi and Young (2013) identify two forms of interactions for hybrid SD-DES models. They introduce these based on the way the two modelling paradigms interact within a model, classifying them as ‘cyclic’ or ‘parallel’. With respect to cyclic interactions, they state (2013, p. 55): “There are no interactions between SD and DES during run time. They interact with each other only after completion of their individual run.” This definition aligns with both the sequential and interfaced design classes making no distinction between them. As demonstrated in Chapter 6, however, it is proposed here that sequential and interfaced are distinctly different hybrid design classes both of which fall within their definition for cyclic interactions. In regards to parallel interactions, they state (2013, p. 55): “In this mode, SD and DES models are run in parallel while information is exchanged during run time”, which aligns to the integrated design class.

The two categories of interaction defined by Chahal, Eldabi and Young form part of a conceptual framework for hybrid SD-DES model design, which, providing an up-to-date contrast to this thesis, will be evaluated further in Chapter 6. As highlighted in this chapter (see also Swinerd and McNaught (2012a)), by Chahal, Eldabi and Young (2013) and by Viana, et al. (2012), the specific focus of design classes for AB-SD hybrid models and interactions for SD-DES hybrid models could be relaxed to cover a wider combination of modelling paradigms. The potential for broader application and comparisons between studies is also discussed in the concluding chapter.

The three design classes defined here refine that originally proposed by Shantikumar and Sargent (1983) in a manner consistent with that described by Martinez-Moyano, et al. (2007) and Chahal, Eldabi and Young (2013). As will be demonstrated, however, examples of all three design classes can be found in the literature and, consequently, at least three classes are required to fully capture the architectural description within the design transition for hybrid AB-SD models. Based on the review presented, it is proposed that these design classes provide a unifying description of architectures for computer simulation models that use this modelling combination.

In considering designs for the complementary use of SD and DES, Morgan, Howick and Belton (2011), propose terminology for reflecting multi-method approaches (Morgan, Howick and Belton, 2011, p. 2719):

- Isolationism – the use of a single method;
- Parallel – triangulation of results using different methods;
- Sequential – the use of one method before the use of another;
- Enrichment – enhancing the primary approach taken with other methods;
- Interaction – relaxation of paradigm boundaries; and
- Integration – combined multi-method to "form a new approach."

These provide a useful cross-reference for the analysis of design architecture presented here for hybrid AB-SD models.

5.2 Suggested Categories of Hybrid Simulations

Having reviewed the literature and compared to other fundamental descriptions of model design as introduced in the last sub-section, three classes of design for hybrid AB-SD simulation are proposed. These are shown schematically in Figure 5-3. Examples of where these design classes have been implemented are described in the following sub-sections for integrated, interfaced and sequential classes, respectively.

With reference to Figure 5-3, the integrated class incorporates feedback between modules representing a continuous, fluid process. Modules within the interfaced class may be run in parallel with their outputs combined as required to represent the desired output as a function of time. In the sequential class, one module has to be run first and its output then fed to the next. The feedback arrows between modules in the integrated class and the arrows from modules to output in the interfaced class do not constrain flows to a single point in time. Indeed, the expectation is that such flows will usually take place several times during simulation. Only in the sequential class is the flow restricted to a single time point.

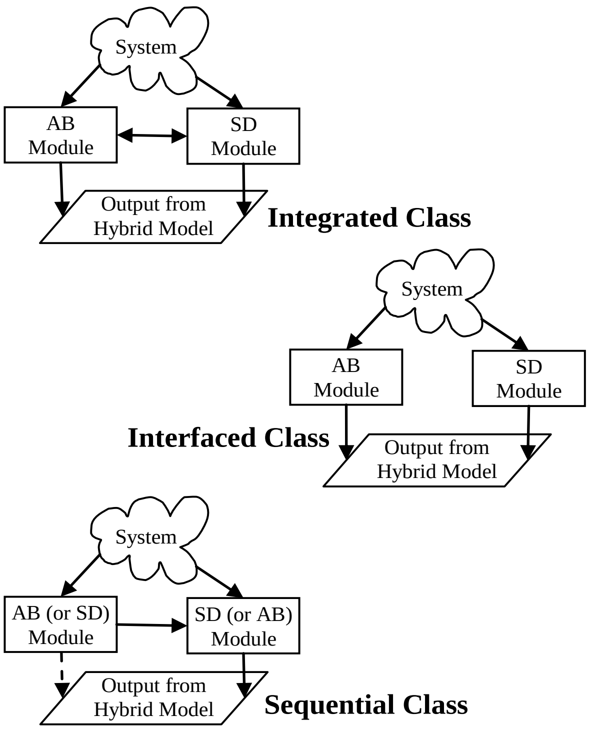

Figure 5-3: The proposed three classes of hybrid AB-SD simulation

5.3 The Integrated Hybrid Design

Not all of the examples presented here of the AB-SD integrated hybrid design explicitly use different simulation paradigms within the model architecture. Three, Sterman (1985), subsequently Steman and Wittenberg (1999), Akkermans (2001) and Dugan (2008), are included that were implemented entirely in an SD environment using the agent-oriented SD approach described in sub-section 2.5.1. As discussed later in this chapter, it is debatable whether such models should be considered truly hybrid or not. They are, however, included for completeness as they do contribute to underlying fundamental design concepts.

Through the literature review, it has been found that there are at least three options available to implement the AB-SD integrated hybrid design concept where:

- an SD module is built within agents of an ABS module ('agents with rich internal structure');
- a stock level within an SD module is used to bound an aggregate measure of an ABS module ('stocked agents'); or
- an aggregate measure or observation of an ABS module is used to influence a parameter within an SD module ('parameters with emergent behaviour').

Examples of each of these implementations are provided below drawing from a diverse selection of application and or research domains.

Schieritz and Gröβler (2003) – Application: Supply chain dynamics

Schieritz and Gröβler (2003) describe an explicit integrated hybrid simulation model for supply chains with SD models representing company decision-making and the links between companies within the supply chain modelled using an AB model. They chose this form of design because the structure, i.e. the interconnected relationships between companies within the supply chain, changes with time and they did not consider this suited a purely SD representation (an argument also put forward by Kortelainen and Lättilä (2009) for their model of competing companies operating within technology markets). They, therefore, complement the SD approach with ABS modelling in order to increase the flexibility of the model to better represent supply chain connectivity as a function of time. In this case, two software packages, namely the Vensim™ SD package and the eM-Plant™ or RePast™ ABS package, were used together in order that the hybrid design could be implemented; the integration of these tools is described by Gröβler, Stotz and Schieritz (2003). Their approach provides a powerful visualisation of the emergent relationships developed in supply chains. It is also worth noting that the implementation of integrated hybrid designs is readily achieved through products such as AnyLogic® (The Anylogic Company, n.d.) or, in the case of agent-oriented SD models, through direct coding such as in the Sterman and Akkermans examples that will be described later. Where a spatial dimension is required within a simulation, then hybrid modelling within an ABS package such as Repast™ or a multi-paradigm package such as AnyLogic® or Netlogo, for example, is likely to provide the simplest implementation, avoiding the need for interfacing disparate modelling tools.

An illustration of this type of integrated hybrid design, where an SD module is integrated within each agent of an ABS module, is provided at Figure 5-4. In this figure, one of the agents is magnified, revealing its internal structure to be an SD model. In the case of Schieritz and Gröβler's hybrid model, the agents are links between companies. However, the representation in Figure 5-4 is a generic representation of the concept.

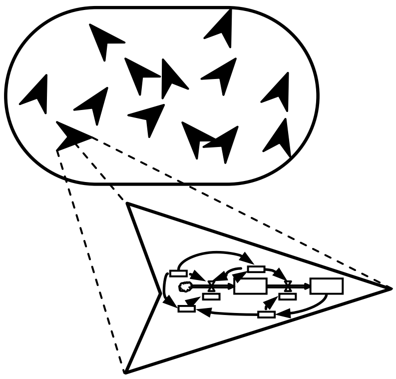

Figure 5-4: An integrated hybrid design concept representing an implementation of agents with rich internal structure

Gaube, et al. (2009) and Verburg and Overmars (2009) – Application: Land change science

The SERD model described by Gaube, et al. (2009) in a special issue of the Landscape Ecology Journal (Milne, Aspinall and Veldkamp, 2009) has a different type of integrated hybrid design. This model has been designed to represent coupled socio-ecological systems in land-change science for a defined region of Austria. It primarily consists of three modules:

- an ABS module representing decision-making by farmsteads, government authorities and 'other important actors' referred to as the ABM;
- a spatially explicit land use module that represents individual parcels of land and is referred to as the LUM; and
- an integrated stock and flow socio-ecological module of aggregate Carbon and Nitrogen flows, referred to as the SFM.

The potential feedback mechanisms within the model are described as:

"*Feedbacks between the ABM and the SFM mostly proceed via the LUM. For example, if farmers decide to change how a parcel of land is used, this affects the area given over to a defined land use (e.g. cattle grazing) and possibly the farming intensity (e.g. amount of* *fertilizer per hectare and year). Direct feedback between the ABM and SFM modules can also occur. For example, households or companies may switch between fuels (e.g. heating oil or wood) and thereby affect the system's C [carbon] balance*."

(Gaube, et al., 2009, p. 1152).

The LUM module was implemented using a GIS mapping system and standard commercial database software, whilst the ABM and SFM modules were implemented within the AnyLogic® simulation software. The mapping module reflects the spatial results of management decisions made within the ABS module for land use allocation. The SERD model, therefore, represents both the 'stocked agent' and 'parameter with emergent behaviour' flavours of integrated hybrid design where, for example, the implication of net carbon and nitrogen flows impact local decision-making and where the aggregate representation of local decisions impact the system at a higher level of the system hierarchy (or scale), respectively. These forms of implementation are illustrated in Figures 5-5 and 5-6.

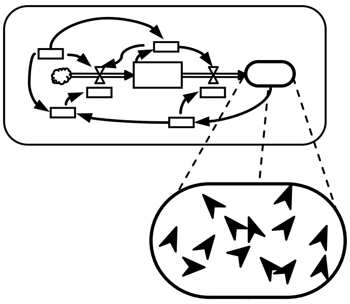

Figure 5-5: An integrated hybrid design concept representing 'stocked agents'

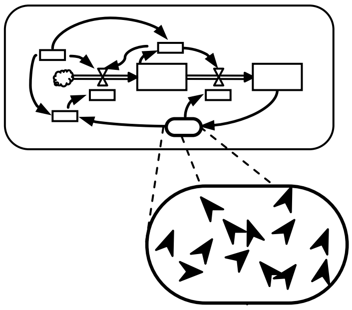

Figure 5-6: An integrated hybrid design concept representing 'parameters with emergent behaviour'

The land change science work as reported by Verburg and Overmars (2009) can be represented by the 'stocked agent' integrated hybrid design. In this concept, the AB model is bound by an aggregate stock level such as products or land use classification, for example. Within the defined bound of the aggregate stock level, detailed information can be made available through observation and analysis of agent behaviour. They chose a hybrid approach for their Dyna-CLUE model in order to explicitly capture cross-scale coupling between local, regional and national aspects of the system. They considered that aggregate models were unable to adequately capture local land change responses to regional or global demand or policy.

On first inspection, the Dyna-CLUE model looks to provide an example of the interfaced hybrid design concept. However, when the time-stepping nature of the model is considered, there is sustained feedback and so this model is assessed to be an integrated design aligned to the 'stocked agent' implementation as illustrated in Figure 5-5. The difference between the implementation here by Verburg and Overmars and that reported by He, et al. (2004) with respect to the LUSD model is slight and yet they fall within different hybrid design categories. In the case of the LUSD model, the national scale of land demand was determined for the 50-year period considered and then the local response to that modelled such that national demand was satisfied. In the example with the Dyna-CLUE model, it is used to iterate between national and local models at each time step.

Kieckhäfer, et al. (2009) – Application: Production strategy in the automotive sector

Kieckhäfer, et al. (2009) describe their integrated hybrid model which represents product portfolio strategies for European automotive manufacturers responding to regulatory requirements for CO2 emissions of new vehicles; the model also incorporates the availability and price factors associated with crude oil. They present a scenario where manufactures have to use a parallel strategy for manufacturing cars with either conventional or alternative fuel-powertrain technology. Their analysis recognises three classes of actor, namely manufacturers, legislators and customers, and the dynamics between them. They present an integrated model comprising SD and ABS modules with the interaction from SD module to ABS module capturing the impact of production costs on car sale price and the influence of fuel price on consumer choice of vehicle technology. The interaction from ABS module to SD module captures the impact of product class sales on manufacturing decision making. This model captures the concepts presented in Figures 5-5 and 5-6.

Chaim and Streit (2008) – Application: Pension fund governance

Whilst the detailed interactions of the ABS and SD models are not described explicitly by Chaim and Streit (2008), individual decision-making of an agent population is modelled using fuzzy logic to represent their decision to participate, or not, in the pension fund. Demographic factors such as age, income and health are factored into the representation of the agents as well as their ability to interact with government, which is also represented as an agent. An SD model is used to represent the governance of the pension fund using an asset and liabilities model that is influenced by the emergent dynamics of the population. The SD model uses aggregate measures influencing assets and liabilities such as financial contributions made, potential for future financial contributions based on age and salary projections, payments to those retired and future liabilities for payments based on mortality predictions of those retired.

Sterman (1985), Sterman and Wittenberg (1999), Akkermans (2001), and Duggan (2007) – Application: Agent-oriented SD modelling

The three examples of agent-oriented SD modelling introduced in sub-section 2.5.1 are considered next but in the context of design class categorisation. Whilst, as already discussed, these examples may not be classified as hybrid simulation models, the underlying design philosophy for each does inform this review; and so are included for completeness.

As described in more detail earlier in this thesis, Sterman (1985), and later Steman and Wittenberg (1999), describes a model for the birth, evolution and death of scientific paradigms based on the theories of Kuhn. In this model, the scientific paradigms can be considered as 'agents with rich internal structure'. The level of confidence held in a paradigm is a key property of each agent and determines its potential to attract researchers and hence sustain its existence and standing in the scientific world. While agents are generated randomly with randomly sampled inherent strengths, the rate of agent generation depends on the state of the dominant paradigm. Ultimately, the behaviour of the model can be shown to be driven by a number of interacting feedback loops.

Akkermans (2001) models a three-tier decentralised supply chain network where companies, referred to as actors, are the agents within the design. Ten original equipment manufactures feed an end market (also considered an agent) and are, in turn, supplied by a further two tiers in the supply network. Akkermans' modelling objective is to assess the impact of actors balancing short-term and long-term relationships with suppliers and customers in the network, and represents decision-making within each agent. On reflection, he reports (2001,

p. 8) that, “it appears feasible, and even advantageous, to implement AB models within a SD environment.”

Duggan’s ‘simulator for continuous agent-based modelling’ (Duggan, 2007) is a method for building hybrid models within an SD modelling framework. A case study is provided of a competitive market that includes a social network. In this, three classes of agent within a population of 100 decide whether to align to one of two companies. This example explores the concept of ‘agents with rich internal structure’.

Further examples of integrated hybrid designs can be found in SD-DES hybrids such as the two reported examples for production planning by Rabelo, et al. (2003) and Venkateswaran, Son and Jones (2004).

The illustration at Figure 5-7 brings together the examples highlighted above with the three types of implementation represented, showing how they all fit within the generic integrated hybrid class. It can be seen that combinations of the three possible implementations can be used to represent scale within the system being modelled (see sub-section 4.1). Integrated feedback within these models is highlighted with the greyed block arrows. In the case of ‘agents with rich internal structure’ and ‘parameters with emergent behaviour’, the flow of information between SD and ABS modules can be bi-directional. In the case of the ‘stocked agent’ implementation, however, information flow will tend to be from the SD module to the ABS module only, with the net benefit being a representation of local (including spatial) or individual behaviours. It is important to note that the process of feedback between the SD and ABS modules within these three interpretations of the integrated design class is not constrained. Feedback is the key feature that provides for an integrated hybrid approach to simulation.

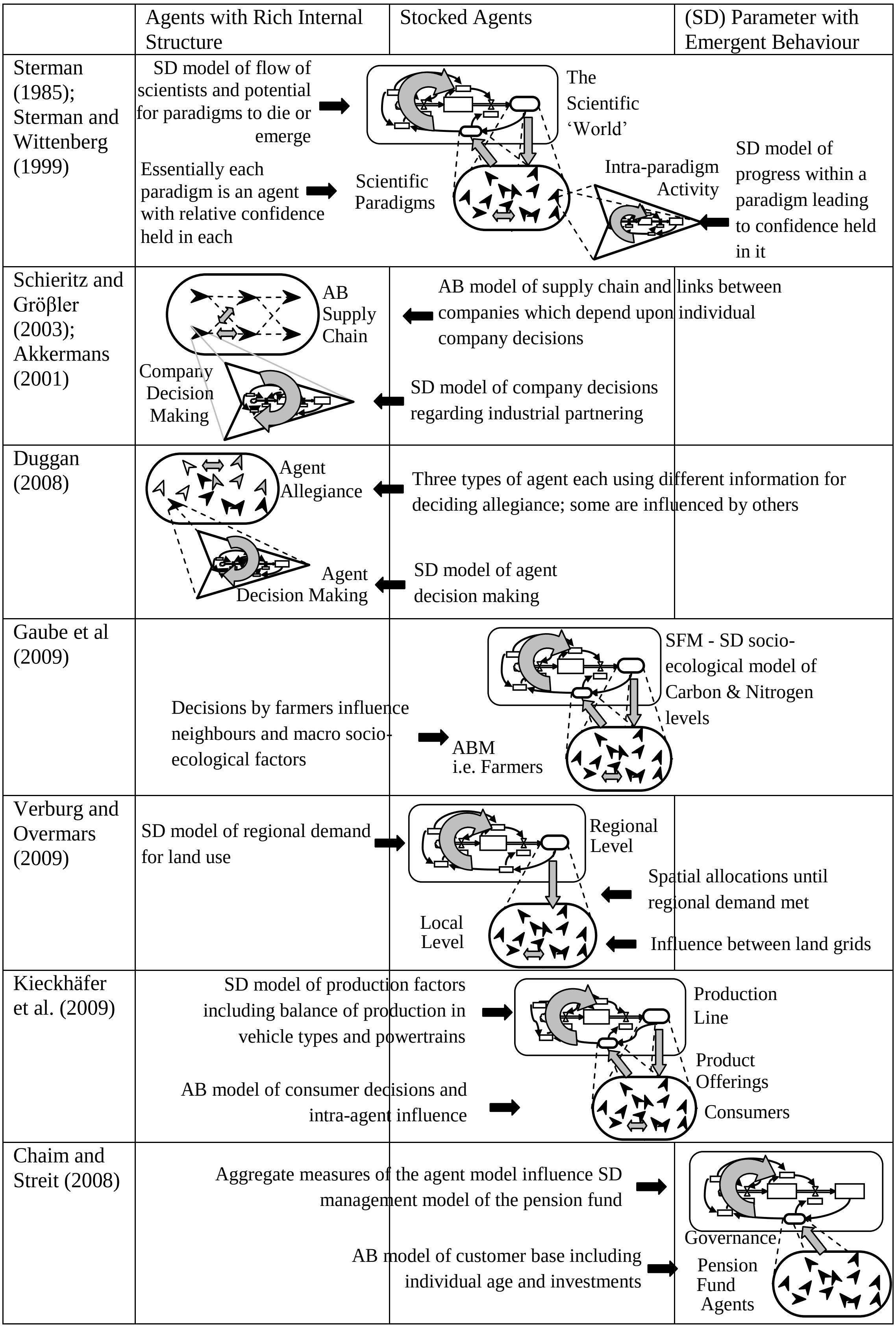

Figure 5-7: Representation of reviewed models that fall within the integrated hybrid design

5.4 The Interfaced Hybrid Design

Based on this review of the hybrid AB-SD literature, the view of Shanthikumar and Sargent (1983) that there can be a fine line between what falls within one hybrid design category and another is supported. At the time of conducting this review, and after careful consideration of described design implementation, no examples comprising SD and ABS modules for this design class were found in the published literature: although an example has subsequently been implemented by the author as presented at Chapter 6.

Dubiel and Tsimhoni (2005) – Application: Provision of information at public venues

Whilst their modelling combination is not the primary focus for this review, Dubiel and Tsimhoni (2005) describe a hybrid simulation that comprises ABS and DES modules. Within the ABS module, an agent looks to travel to a 'goal object', avoiding obstructions and obtaining directions from dynamic information objects (people) or stationary information objects (maps) to get from their starting point to the 'goal'. They can walk all of the way or take a tram for part of the way, the tram being represented within the DES module. If taking the tram, the agent queues at a tram stop and, when a tram arrives, moves out of the ABS module and into the DES module. The agent departs from the tram at a stop after a defined period of time, transitioning from the DES module to the ABS module also. If the agent gets lost, then it returns to its last point of interaction and starts its journey again. There is no direct feedback between ABS and DES modules, although the journey can be faster if the agent learns to take the tram. This model is, therefore, considered to be an example of an interfaced hybrid design as the agent is either walking within the ABS module or is travelling within the DES module; i.e. alternating between independent ABS and DES modules. The net result of total travel time can, however, require output from both modules.

Swinerd (Chapter 6) – Application: Pollution risk to unaware populations

The AB-SD hybrid model presented in Chapter 6 models the risk of populations to spreading pollution where agents in the populations are unaware of that risk. The output of this model can only be achieved by mapping the output of the ABS module of population movement and behaviours with that of the agent-oriented SD module of pollution.

5.5 The Sequential Hybrid Design

A sequential design is where one modelling technique is used to inform the design, use or starting conditions of another. This design class aligns with both Classes III and IV defined by Shantikumar and Sargent (1985). Where there is a choice, they suggest the use of a Class III model in preference to a Class IV model because the analytic model is in general cheaper and computationally more efficient. Whilst this argument probably still holds, ongoing enhancements in both computer power and modelling tools may, arguably, reduce the need for such consideration. Here both Class III and Class IV are considered part of the sequential design class.

Homer (1999) – Application: Workforce planning

Homer describes an analysis of field service strategy for handling work volumes with a staff of mixed training, preparedness and experience. The primary model is an SD representation of the strategic issues to be addressed by a field service company such as demand, workforce scheduling, service quality, customer satisfaction and finance. Part of this model captures the training of the workforce. If all staff were trained to repair all equipment, then a straightforward aggregate ratio could be used to link time spent on training to time spent on revenue-earning activity: however, the workforce considered, as with any workforce, had a mix of experienced and trained staff. Not all staff could repair all equipment and, therefore, a detailed analysis was required in order to determine the readiness of the workforce to service demand. With further analysis, it became apparent that a form of empirical relationship, typically represented within SD models using a table function, would be required for part of this model. Despite a general consensus on the likely shape of the table function, however, there was no hard data available to confirm this. This was overcome by developing a 'micro-scale' agent-based model to replicate the workforce and using this to determine the nature of the table function required in the SD 'macro' model. The paper describes in detail how this was achieved. In conclusion, Homer reflects that (1999, p. 159): "SD model parameters should be estimated using data below the level of aggregation of model variables wherever possible." However, it is not always straightforward especially when using lower aggregate historical data for use in an SD model designed to predict future outcomes beyond the range of past experiences. Here the process of developing a micro-level model for service queuing and task allocation to individual engineers in order to develop a key table function for service readiness was considered successful. Homer reflects that while it was time consuming to complete, the process of doing this produced greater insight into the issues around cross-training and achieved much more stakeholder buy-in than if the table function had been based purely on assumption or judgement.

Schieritz and Milling (2009) – Application: Population dynamics

Schieritz and Milling report the use of ABS to identify and quantify macro structures that can be used within an SD model. The main objective of their paper is to assess the potential to use ABS modelling where either the structure of a system is unknown to decision makers working within that system or their collective mental model cannot be captured. They state that where either condition cannot be fulfilled, then (2009, p. 140) "… it would be difficult to quantify an SD model or to even identify the causal problem structure." They begin by using a relatively simple SD population model as an example in which the level of population size is regulated by the rates of reproduction and death: the reproduction rate being a function of the population level and fertility a function of the availability of resources. They observe, however, that fertility depends upon local conditions and that the SD model can only represent global availability of resources.

Consequently, they build an AB model of a population of agents which can be configured so that all of the agents are either static or mobile. In the static case, the agents deplete their locally available resources and hence their fertility is reduced, which in turn slows the rate of population growth. However, in the mobile case the agents can access resources and thereby maintain fertility levels. In this case, the population grows more rapidly than in the static case and reaches a stable population level where the rates of reproduction and death are in balance. A plot of average fertility versus availability of resources reveals two different relationships that could be used via a table function within an SD model.

They then go on to extend their analysis of population dynamics to the situation where the causal relationships of the SD model are not known. Here they investigate the use of an ABS approach to determine the design of the SD model. However, they state that one prerequisite to this approach is that the policies of the individual agents have to be identifiable. They also note that an advantage of the parallel or sequential use of different methodologies for the analysis of a single problem is the ability to validate results, although they concede that this may require a substantial effort.

He, et al. (2004) – Application: Land change science

In reporting on land use dynamics in China, He, et al. report on the Land Use Scenario Dynamics (LUSD) model which incorporates SD and Cellular Automata (CA) modules. Within this design concept, the SD module firstly determines national and regional demand for land use based on factors such as land policy, demographics, market demand, the economy, and influence of technology. The CA module then provides a spatial representation of local land allocation to meet the aggregate demand defined by the SD module and considers local factors such as land suitability, land inheritance and the influence of neighbours. The output from the LUSD model is provided by the CA module and is in the form of a geographic map on which land change is plotted.

Generic representations of the sequential designs described are presented in Figure 5-8 for reference.

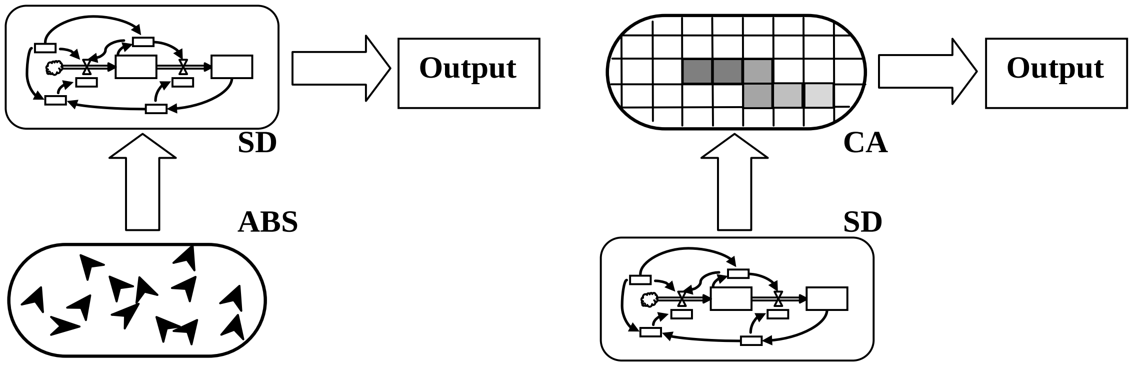

Figure 5-8: Sequential hybrid design concepts using an AB module to inform an SD module and an SD module to inform a CA module

5.6 On the Utility of Hybrid Modelling Design

In conducting the literature review to identify published examples of the three design classes for hybrid AB-SD simulations, underlying factors that appear to shape design choices were identified. In doing so, it is possible to identify the circumstances under which design classes might be used. This analysis of utility draws together the general framework described in Chapter 4, used to capture the content of the conceptual model through 'individuals', 'observables' and the 'environment', with the definition of design classes discussed in this chapter (integrated, interfaced and sequential). Linking the conceptual model (CM) and model specification artefacts of the general modelling process as defined in Figure 2-5, a decision process for the utility of hybrid AB-SD models is defined in Figure 5-9; decisions made during the design transition.

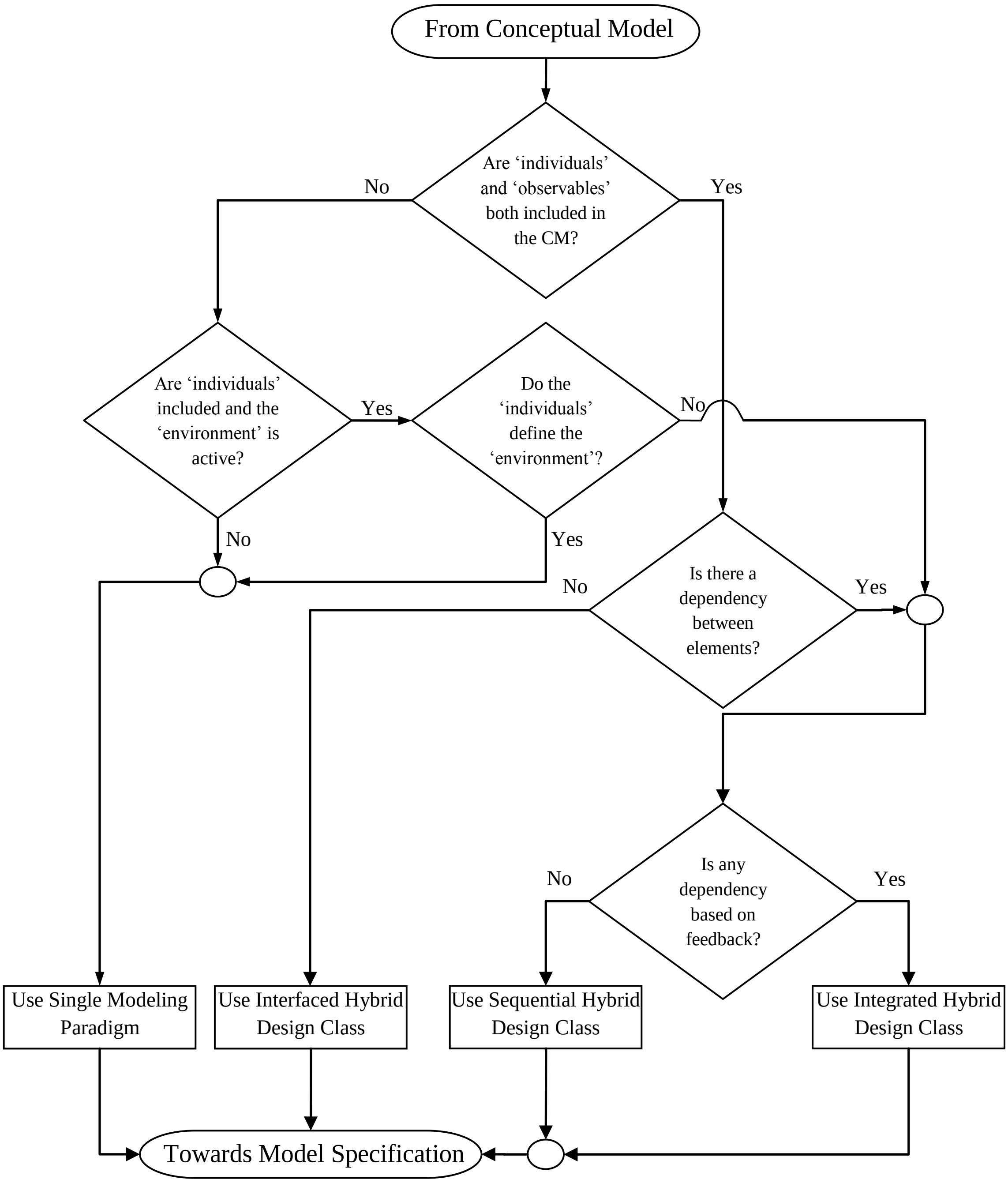

Figure 5-9: General decision process to help determine a suitable class of hybrid AB-SD model

Initially, the test is to confirm whether both individuals and observables are included in the content of the conceptual model. If so, then specification of a hybrid AB-SD model could be a viable option. If not, then specification of a hybrid AB-SD model remains a viable option if individuals are included and, recognising that SD could be used to implement the environment, the environment is 'active' in accordance with the definition of Lorenz and

Jorst (2006). In ABS, the society of agents can represent the environment with which agents interact, in which case a specification for a single-paradigm ABS model may suffice. Equally, where individuals are not specified, then a specification for a single-paradigm SD model may suffice.

Having determined that a hybrid AB-SD model is a viable option for the modelling project, the next step is to determine which design class is most appropriate. If there is no interaction between elements, yet the output of the model requires both individuals and observables, then an interfaced design is the preferred option. In the review reported by Swinerd and McNaught (2012a), no examples of hybrid AB-SD models designed according to the interfaced design class were found. For reference, however, an example model is presented in Chapter 6. If there is any bi-directional flow of information between individuals and observables elements or an individuals element and active environment, then feedback is incorporated in the design and so an integrated design class should be specified. Without feedback, a sequential design class is more appropriate. These decisions will shape the model specification, either directly or following further design effort.

Having settled on the design class if using a hybrid model, the next issue will be to determine what modelling paradigms are best suited for the modules within the model. Formal methods, such as Osgood (2006) on quantifying the intrinsic dimensionality of systems, or experience may help inform such modelling choices. Those without experience, either because they are new to simulation modelling or because they have limited experience will require further guidance. Whilst further research is required to inform such decisions, an initial analysis comparing modelling paradigms is presented next.

5.7 Comparing Modelling Paradigms

Comparisons of modelling paradigms and their associated methodologies have been made from time to time. As pointed out by Morecroft and Robinson (2005), when comparing SD and DES, comparisons will have differing perspectives and will often be made by researchers who are expert in one paradigm but not necessarily in the others with which comparisons are being made. Whilst Morecroft and Robinson, who are expert in SD and DES, respectively, looked to compare the nature of explanations and insights that can be derived from these approaches, earlier comparisons cited by them focussed on other aspects such as technical differences (Coyle, 1985; Mak, 1992; Brailsford and Hilton, 2000; Pidd 2004 cited by Morecroft and Robinson, 2005) or conceptual differences (Lane, 2000 cited by Morecroft and Robinson, 2005) for example.

Schieritz and Milling (2003) provide a useful comparison of SD and ABS in an aptly titled paper 'Modeling the forest or modeling the trees' [sic]. Highlighting the potential of the Anylogic® multi-paradigm modelling tool, Borshchev and Filippov (2004) present the differences between all three paradigms against a scale of abstraction. Lorenz and Jost (2006) compare all three paradigms, discussing their underlying assumptions and technical differences. They emphasise the importance of asking what the purpose of the final model is in addition to accounting for the nature of the system being modelled (as represented in Figure 2-1). More recently, Behdani (2012) considers the application of the three paradigms in the context of supply chain modelling, with due consideration to the impact of socio-technical interactions within the supply chain.

There are, therefore, many factors and perspectives that will inform the selection of a modelling paradigm or paradigms. Not unreasonably, the terms 'natural' or 'best' choice are often used to capture reasoning for selecting or using specific paradigms; Morecroft and Robinson (2005, p. 8), Swinerd and McNaught (2012a, p. 119), Viana, et al. (2012, p. 3) or

Nikolic, Simonovic and Milicevic (2013, p. 407) for example. This sense of a natural choice is captured in Figure 5-10. These word art images were created by counting the frequency of words used in positive verbatim descriptions of modelling paradigms in the comparison studies cited above by Morecroft and Robinson (2005), Schieritz and Milling (2003), Borshchev and Filippov (2004) and Lorenz and Jost (2006): words had to be used at least twice in order to be included. Only positive comments are included as it is not necessary to know what a paradigm may not be able to do in this case. The whiteness and font size of the key words capture a sense of what each paradigm is most often associated with.

Figure 5-10: 'Natural' descriptors for SD, ABS and DES modelling paradigms

By ordering these words into a Venn diagram, one can immediately start to identify similarities and differences between these modelling approaches; as described by the studies indentified above.

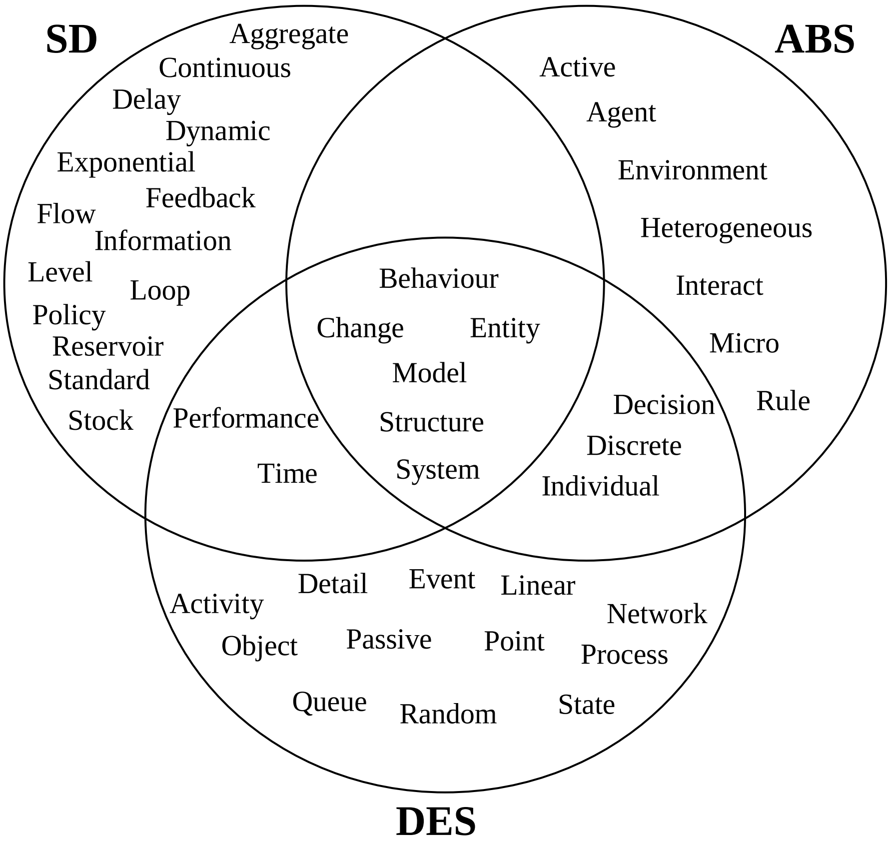

Figure 5-11: Venn diagram of words used to describe SD, ABS, and DES modelling paradigms

All approaches are characterised by: the system and its structure; modelling; entities; change and behaviours. The dual-paradigm intersections indicate common ground through which modelling approaches might be usefully combined along with the common themes identified at the intersection for all approaches:

- DES-ABS - An individual perspective with a focus on decision making, within a discrete sampling space; or
- SD-DES - system performance over time; or
- SD-ABS - Nothing in common other than what they share with DES.

SD and AB modelling have been widely applied across many domains to predict system behaviour using either deductive SD or inductive ABS approaches. As such, these paradigms represent complementary approaches to modelling, which when combined with the fact that they share little in common may explain the rapid rise in publications reported in ; i.e. they naturally complement each other, each providing a unique perspective.

5.8 Chapter Summary

Building on analysis to capture the content of conceptual models presented in Chapter 4, this chapter has completed the description of the design transition by:

- Identifying design classes that describe the architecture of hybrid AB-SD models including the integration of modules;
- Reporting a wide ranging review of published models to secure a general classification of integrated, interfaced and sequential design classes;
- Proposing a decision process to aid selection of one of these design classes; supplemented by initial advice on how to select specific modelling paradigms to incorporate within a design.

Chapter 6 RESEARCH EVALUATION

The objective of this chapter is to present an evaluation of the research presented in previous chapters. This is split into two aspects: an evaluation against other published literature, and evaluation through demonstration using a modelling case study.

The evaluation against published literature is further split into two parts. Firstly, a comparison of the evaluation criteria for design guidance and the conceptual framework for hybrid SD-DES model design, referred to hereafter as the conceptual framework, proposed by Chahal, Eldabi and Young (2013) is made with that reported in this thesis. Given that the conceptual framework was published during the preparation of this thesis, this comparison serves as a timely and independent benchmark. Furthermore, given that it considers the modelling combination of SD and DES, the comparison with the conceptual framework also serves to inform whether design guidance for hybrid simulation modelling can be extended to any combination of SD, DES and ABS. Secondly, more general comparisons are made, looking at broader aspects of providing guidance for the design of hybrid models; this comparison again includes the work of Chahal, Eldabi and Young (2013) and a response to Balabam and Hester (2013) who have previously cited and commented on the utility of the design classes proposed by Swinerd and McNaught (2012a).

6.1 Requirements for Conceptual Frameworks

Prior to defining their conceptual framework, Chahal, Eldabi and Young (2013) propose criteria for evaluating design guidance for hybrid (SD-DES) models. These criteria are based on three questions, induced from a review of published literature:

- Why (why hybrid simulation is required)?
- What (what information is exchanged between SD and DES models [modules])? And

- How (how are SD and DES models [modules] going to interact with each other over time to exchange information)?

Against these evaluation criteria, they develop their conceptual framework and demonstrate its implementation through a case study. As with the methodology used for this research, they used an inductive research approach, drawing on the published literature. Before reflecting on the evaluation criteria questions posed by Chahal, Eldabi and Young (2013), a side-by-side comparison is made, see Table 6-1, between that conceptual framework and the guidance developed in this thesis.

Table 6-1: Comparing the conceptual framework of Chahal, Eldabi and Young (2013) with the general guidance presented in this thesis

Conceptual Framework of Chahal, Eldabi and Young (2013)	Thesis Mapping	Comments
Phase 1: Problem Identification	Figure 2-1, the General Modelling Process and Table 4-1, Conceptual Modelling.	Conceptual modelling as defined by Robinson (2012).
Identify overall objective		
Need for assistance?		
Goal?		
Internal and external influences?		
Decompose in to smaller objectives	Figure 4-3, the General Framework.	One environment element per model plus any number of individuals and observables elements.
Method selection	Sub-section 5.7.	Further research is required to support the selection of modelling paradigms. Although, this selection may become easier with increased fidelity in decomposing to smaller objectives (to more modules).
Fit is the conjunction of problem, system and methodology		
Are there interactions?	Figure 5-9, the Decision Process.	The nature of interactions determines whether a hybrid approach is required and, if so, what design class is most appropriate within which to architect the hybrid simulation model.
Phase 2: Mapping Between Modules	Figure 4-3, the General Framework.	One environment element per model plus any number of individuals and observables elements.
Development of modules		
Identification of interaction points		
Inputs and outputs		
Variables		
Influencing variables		
Formulation of the relationship between interaction points	Figure 4-3, the General Framework.	Supplemented by detailed definitions of interfaces as illustrated in Figures 4-5 and 4-6 through the inclusion of interfaces defined as: Type: Name [initial value, range of values, units].
Direct replacement	Figures 5-4, 5-5, and 5-6, Design Concepts.	An area for further research.
Aggregation / disaggregation		
Causal		
Mapping interaction points to modules	Figure 4-3, the General Framework.	Supplemented by Figures 5-4, 5-5, and 5-6 Design Concepts.
Phase 3: Identification of mode of interaction	Figure 5-9, the Decision Process.	The nature of interactions determines whether a hybrid approach is required and, if so, what design class is most appropriate within which to architect the hybrid simulation model.
Modules coupled in time and space?		
These interactions important to overall objective?		
Parallel interactions	Figure 5-3, Design Classes.	Integrated Design Class.
Cyclic interactions		Interfaced and Sequential Design Classes.

As can be seen in Table 6-1, the conceptual framework comprises three phases, the numbering and titling of which strongly suggests an order. This order is reinforced in the case study presented by Chahal, Eldabi and Young (2013) as they move step-by-step though the conceptual framework. The research conducted for this thesis suggests that the designer is more likely to iterate their design rather than follow a prescribed order. This view is supported by Robinson (2012) who makes the same observation when describing the general modelling process.

It is proposed that the early part of the conceptual framework, where the overall modelling objective is established, aligns strongly to the general modelling process described in Chapter 2 and to conceptual modelling described by Robinson (2012) and implemented in Table 4-1 for managing literature review in this research. The decomposition in to smaller modelling objectives aligns well with the general framework (Figure 4-3), using multiple instances of individuals and observables elements. Citing Pidd's rule of 'divide and conquer' (Pidd, 2001 cited by Chahal, Eldabi and Young, 2013), the general framework allows the inclusion of modules integrated within the bounds of defined interfaces. Such division also supports the potential for code re-use and sensitivity testing through module exchange. Method selection is arguably the least well developed aspect of both the conceptual framework and that presented in this thesis. Further research should be undertaken to establish selection criteria for modelling methods. This is a complex area as any criterion would need to accommodate personal and experiential biases.

Establishing the need for hybrid modelling to begin with is represented in both the conceptual framework and here through the decision process (Figure 5-9). There is a difference here though, where Chahal, Eldabi and Young (2013) cite the guidance of Fahrland (1970) and Lee, et al. (2002), who suggest that a hybrid modelling approach may not be needed where there are no interactions between SD and DES models (modules). The research here suggests that the interfaced design class is a valid hybrid design even though there are no interactions between modules during simulation. This is considered to be a valid hybrid approach as the output from the model relies on a contribution from both modules and is incomplete without those contributions. Practical examples of this design class for SD-DES hybrid modelling (Dubiel and Tsimhoni, 2005) and for AB-SD hybrid simulation modelling (see the case study later in this chapter) both underline this finding.

Phase 2 of the conceptual framework almost entirely maps to the general framework proposed here. The interfacing of elements within the general framework clearly demonstrates the mapping of modelling methods to modules. The formulation of relationships between interaction points supplement the design concepts presented in Figures 5-4, 5-5 and 5-6; although, as with method selection, there is scope for further research here. Formulations, based on direct replacement, aggregation / disaggregation, and causal relationships, positively complement the design concepts of stocked agents, agents with rich internal structure and parameters with emergent behaviour presented in this thesis.

Phase 3 shows strong agreement with the decision process (Figure 5-9) and the design classes (Figure 5-3). There a two noteworthy differences here. Firstly, as mentioned previously, the interfaced design class aligns to their definition of cyclic interactions and, secondly, their basis for selecting a model design based on parallel interactions (aligned to the integrated design class) differs. They propose the importance of modules being coupled in time and space, whereas here in the decision process the requirement is based on feedback. The basis for feedback in this research explicitly includes time, but may or may not include a spatial component.

Against the evaluation criteria of Chahal, Eldabi and Young (2013), it can be demonstrated that this framework positively complies:

- Why (why hybrid simulation is required)?
    - Hybrid modelling can be rejected in the decision process (Figure 5-9). The decision process then goes further in identifying when different types of hybrid AB-SD models would be most appropriate.
- What (what information is exchanged between SD and DES models [modules])?
    - Interfaces are established in the general framework (Figure 4-3), supplemented by more specific design concepts for interfacing modules presented in Figures 5-4, 5-5 and 5-6. Further research could be undertaken to build upon the formulation of relationships at interactions points proposed by Chahal, Eldabi and Young (2013) and the design concepts presented here.
- How (how SD and DES models [modules] are going to interact with each other over the time to exchange information)?
    - Established through the proposed design classes (Figure 5-3).

The general level of agreement between the conceptual framework and the guidance provided here is good. Only in two aspects do they differ where a defence for those differences has been presented. Two areas that are common to both approaches have been highlighted for further research: firstly, to develop guidance for selecting modelling methods and, secondly, to enhance the definition of relationships at the interface between modules.

6.2 Modelling Case Study

Here, a modelling case study is used to demonstrate the implementation of the three design classes for hybrid AB-SD simulations introduced in Chapter 5. The case study is deliberately chosen as a simple abstract scenario in order to retain focus on the implementation and comparison of the design classes, rather than on the case study itself. This case study also draws upon the general framework introduced in Chapter 4 for representing the content of the conceptual model (and hence modules in the model). The decision process reported in Chapter 5 is used to demonstrate how the content of the conceptual model can be represented using each design class.

Initially, the modules that are used to build the simulation models are described. Then, they are combined to make a model in accordance with each design class as illustrated in Figure 6-1. Only one ABS and one SD module are combined here. An option for extending the model with an additional module is discussed in order to illustrate how general design guidance may facilitate multiple modules if required.

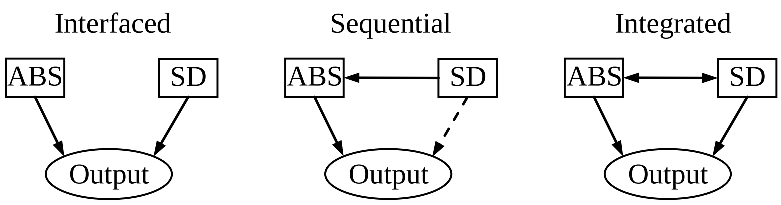

Figure 6-1: Interfaced, sequential and integrated design classes

The case study represents a hypothetical pollution scenario in which the aggregate risk to two populations is measured. Each population comprises the same number of agents but each has a different social norm: one whose agents look to keep their distance from others and one whose agents look to remain in contact with others. The populations comprise, therefore, 'loner' and 'social' agents, respectively.

6.2.1 Implementation of design archetypes

The design classes are implemented by controlling the interface between the populations of individuals and the observable changing spread of pollution. Initially, the populations have no knowledge of the pollution and so, as the pollution spreads, the risk to each population changes depending only upon the packing density of agents and their social norms: this model uses the interfaced design class[5]. In the next iteration, the populations become aware of the pollution and so they look to maintain their social preference whilst also looking to minimise individual risk: this model uses the sequential design class. Finally, the aware individuals add to the spread of pollution once they have themselves been polluted beyond a threshold level: this model uses the integrated design class. These outline design choices are represented in Figure 6-2 using the decision tree for hybrid modelling utility introduced in Chapter 5.

[5] Based on the literature reviews for this thesis and that reported by Swinerd and McNaught (2012a), this is the first known example of a hybrid AB-SD model demonstrated using the interfaced design class.

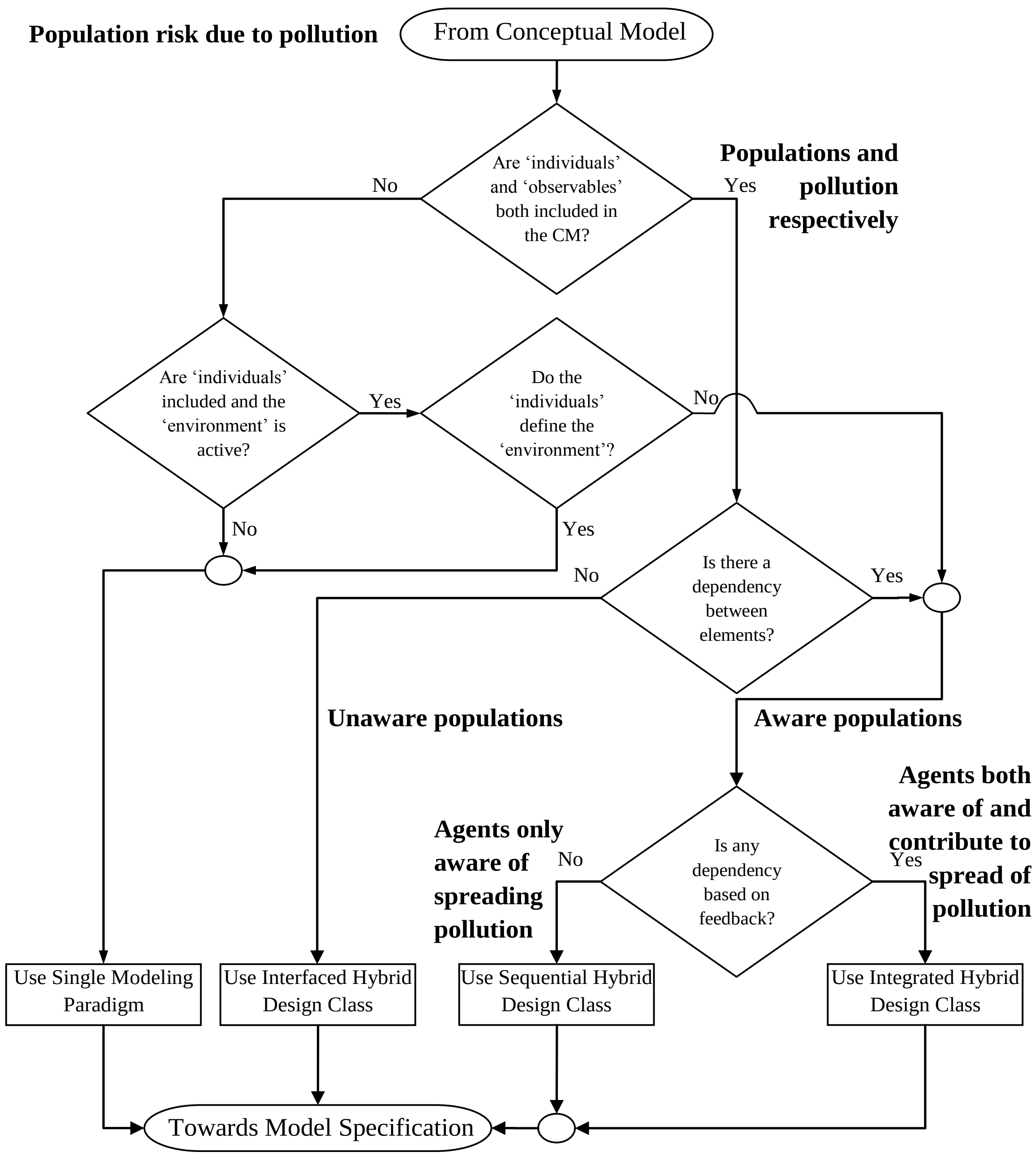

Figure 6-2: Design choices for the case study of population risk due to pollution

Having implemented these models using each design class, the content of the conceptual model was then reaffirmed and represented in the general framework as proposed in Chapter 4 and as illustrated in Figure 6-3. As Robinson observes (2012, p. 6): "the modelling process is interactive in nature (Balci 1994; Willemain 1995; Robinson 2004), the conceptual model is continually subject to change throughout the life-cycle of a simulation study." The advantage in this case, of stopping to reflect on the three models through the general framework, was that the detailed design of the model could be visualised and alternative modelling options identified and considered. As highlighted, it is expected that modellers will iterate a design during the design transition and, consequently, whilst all the guidance presented here should be used, the order and use of guidance will vary from study to study.

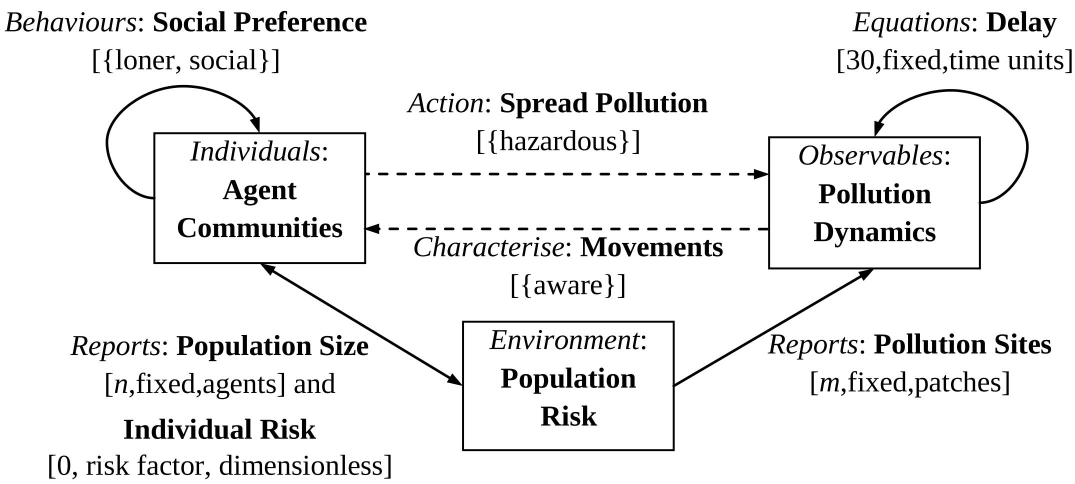

Figure 6-3: Representation through the general framework of the pollution model

With reference to Figure 6-3, the environment is initiated by *n* agents assigned equally to each population and the number *m* of pollution sites: both are fixed for a simulation. Two populations exist, differentiated by their social preference. If hazardous, members of either population can, depending upon the design class implemented, spread pollution. Also depending upon the design class implemented, the pollution dynamics characterise the movements of agents: with pollution dynamics controlled by a fixed time delay. As the simulation progresses so individual risk is reported.

These models were implemented in Netlogo (Wilensky, 1999). The choice of this modelling tool, including a detailed examination of coding hybrid AB-SD models in it, is presented at Annex B for reference. The SD and ABS modules used to construct models implemented in each design class are next introduced.

6.2.2 The SD Module

The default two-dimensional world-view in Netlogo (v4.0.3) (Wilensky, 1999) presents a 32 by 32 wrapped array of contiguous patches. Drawing on the agent-oriented SD concept (Duggan, 2008; Akkermans, 2001; Sterman and Wittenberg, 1999), the colour of each patch is controlled using an oscillatory feedback system as described by the System Dynamics Society (Radzicki and Taylor, 1997) and represented at Figure 6.4.

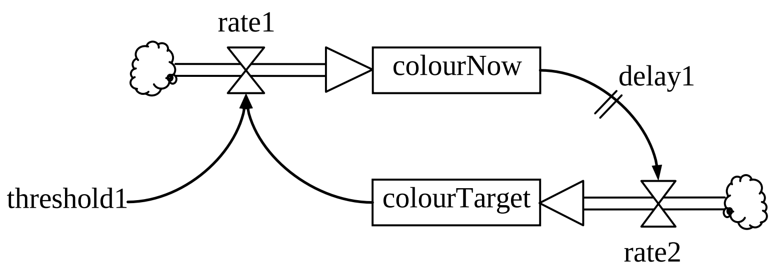

Figure 6-4: Oscillatory feedback system used within the SD module

Looking to track a defined threshold (threshold1), the temporal response of the stock colourNow varies depending upon the imposed time delay (delay1). This system is fully described by the following equations:

rate1(t) = threshold1(t) – colourTarget(t)

rate2(t) = colourNow (t – delay1)

colourNow = colourNow + rate1(t) * dt

colourTarget = colourTarget + rate2(t) * dt

The value of the stock colourNow following a unity step change in threshold1 is illustrated in Figure 6-5 for a number of time delays (delay1) with dt = 0.05. For a delay up to 20 time steps, it can be seen that the system response is a damped oscillation tracking and eventually reaching the target threshold level; however, longer delay may induce a run away response.

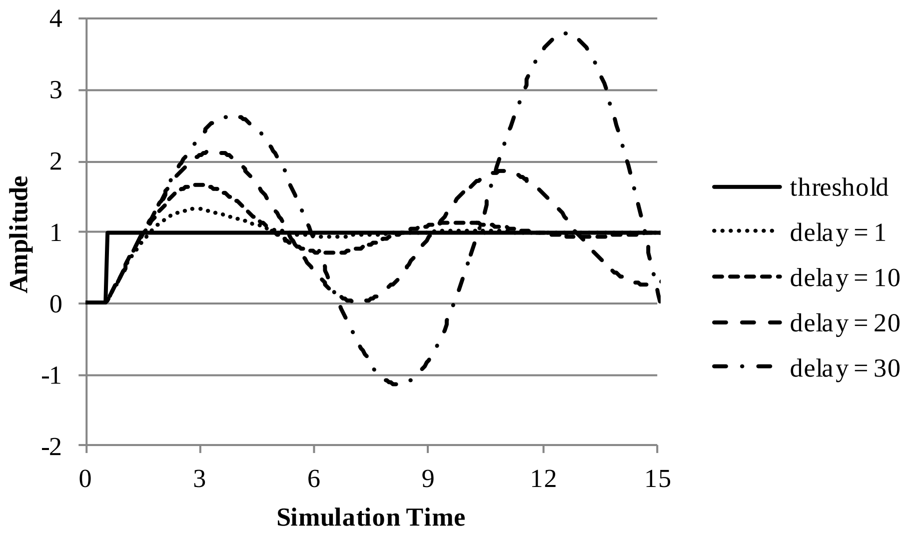

Figure 6-5: Oscillatory response of the SD module for different delays

This SD module is used to define the colour of each patch in the world-view. The mapping used between the colour of a patch and its colour value (colourNow) is presented in Figure 6-6.

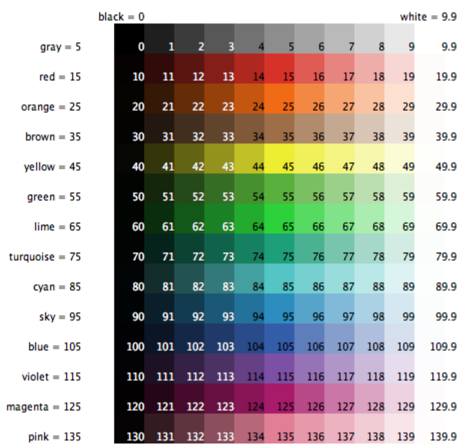

Figure 6-6: Colour map (Wilensky, 1999) (reproduced with permission: Attribution-ShareAlike (CC BY-SA 3.0))

Initially, the colour value for each patch is set to 'lime', i.e. colourNow = 65. A user-defined number of random patches are then modified so that their colour value is set to 'sky', i.e. colourNow = 95. The threshold level (threshold1) is defined for all patches as the mean colour value for the three immediate patch neighbours to the west: therefore, the colour setting for each patch, colourNow, will remain constant unless influenced by a prevailing westerly change. If one considers this world-view to be orientated along the cardinal directions, then wrapping allows for a continuous world whereby leaving an eastern most patch whilst travelling due east next places you at the western edge of the world-view etc.

The two illustrations in Figure 6-7 show the world-view at time step 0 (left) and 100 (right) where dt = 0.05 and delay1 = 10 and three patches are set to ‘sky’ at the outset (Lime and Sky colours are highlighted as a point of reference in case this thesis is viewed in Black and White). In this case the range of colour settings across the world-view after 100 time steps varies between 44.319 and 75.559, i.e. yellow through to turquoise.

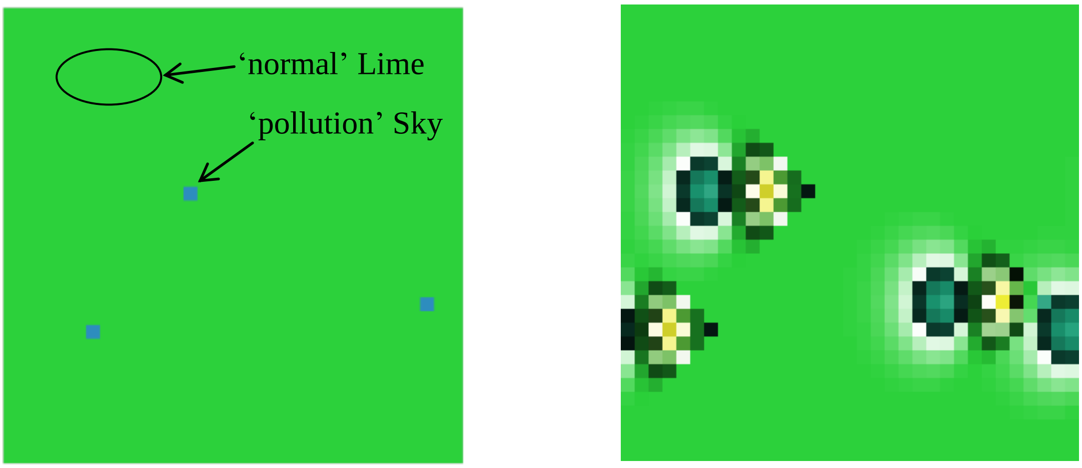

Figure 6-7: World-view before and after 100 time steps for delay1 = 10 and dt = 0.05

World wrapping, as discussed earlier, is evident in the right hand image with the influence of the most westerly ‘sky’ patch leaving the western edge and flowing in from the eastern edge. Changing the delay such that delay1 = 30 results in a different outcome after 100 time steps as illustrated in Figure 6-8 (note: three different patches initially set to ‘sky’).

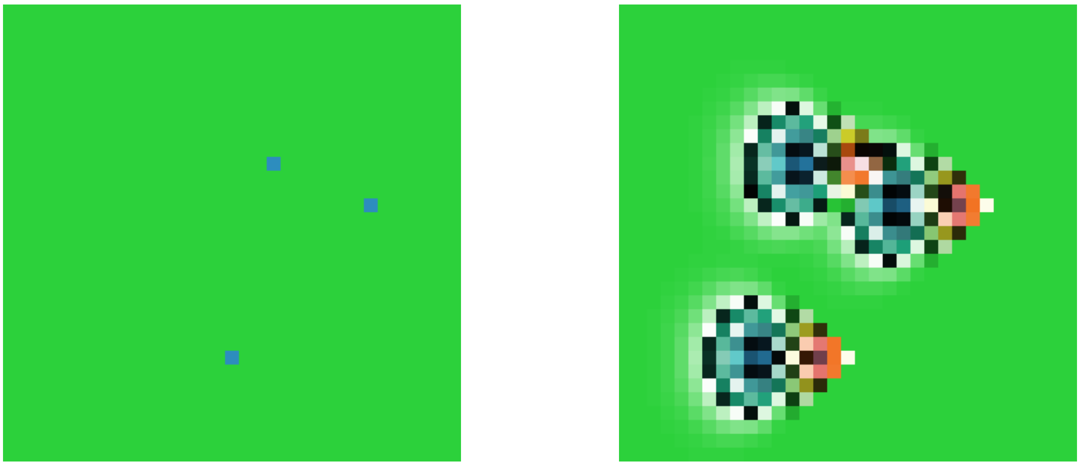

Figure 6-8: World-view before and after 100 time steps for delay1 = 30 and dt = 0.05

In line with expectation, the colour settings for all patches now vary over a wider dynamic range, between 16.678 and 138.776 (red through to pink), and the number of patches influenced has, as a result, also increased. The potential for complex colour patterns to emerge from this relatively simple model is also evident with the influence of two of the three initial 'sky' patches starting to merge after 100 time steps. Using the same seed for the Netlogo pseudo-random number generator, outcomes are repeatable for the same initiation conditions and delay setting.

One might consider this world-view an abstract environment in which variation away from the norm emerges in a prevailing direction; such as pollution in blown air or in flowing water, for example.

6.2.3 The ABS Module

Two types of agent are defined: the 'loner' agent; and the 'social' agent. Loner agents look to keep their distance from other agents whilst social agents look to remain in close proximity to at least one other agent at all times. At the start of a simulation, an equal user-defined number of each agent type is randomly placed in the world-view with each agent facing a random direction. The underlying rules for these agents state:

- Social Agents - If no other agents are within a radius of four patches then face the nearest agent and move two steps forward.
- Loner Agents - If another agent is within a radius of four patches then face the nearest agent and move two steps away.

The state diagram formally describing these agents is defined in Figure 6-9.

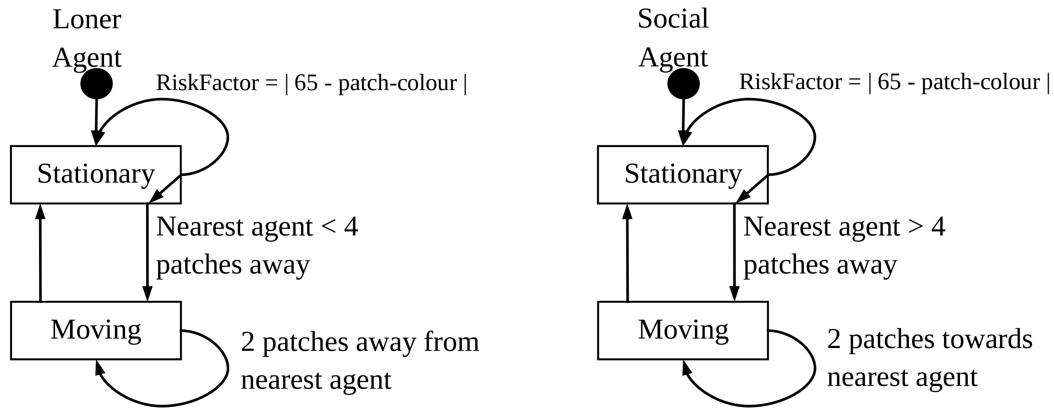

Figure 6-9: State diagrams for loner and social agents

Under densely populated conditions, social agents will tend to be static whereas loner agents will mostly be on the move looking to find their own space.

6.2.4 The Conceptual Model

Before describing simulations modelled with each design class, the conceptual model for this study is represented in Table 6-2.

Table 6-2: Conceptual model for a simulation case study that uses interfaced, sequential and interfaced design classes with the hybrid AB-SD modelling combination

<table>
<tr><td>Author(s) and Reference(s)</td><td colspan="2">Swinerd, C., 2014. On the design of hybrid simulation models; focussing on the agent-based system dynamics combination. PhD. Cranfield University.</td></tr>
<tr><td>Real World Problem</td><td colspan="2">Population risk to spreading pollution.</td></tr>
<tr><td>Modelling Objectives</td><td colspan="2">Visualise the spread of pollution and assess the risks faced by populations with different social norms.</td></tr>
<tr><td>Inputs (Experimental Factors)</td><td colspan="2">Population size, pollution sites, agent hazard threshold and time delay for pollution dynamics. Possible extension to types of information communications.</td></tr>
<tr><td>Outputs</td><td colspan="2">Elapsed time world-views of pollution spread including population distributions.
Aggregate population risk over time.</td></tr>
<tr><td>Content</td><td colspan="2">See Figure 6-3.</td></tr>
<tr><td>Assumptions</td><td colspan="2">Interfaced design: populations unaware of and not contributing to the spread of pollution.
Sequential design: populations aware of but not contributing to the spread of pollution.
Integrated design: populations both aware of and contributing to the spread of pollution.</td></tr>
<tr><td>Simplifications</td><td colspan="2">Only one ABS and one SD module used in model designs.
Only two equally sized populations included.
Agent behaviour is the same for all agents within a population.
Agent movement decision is always relative to the nearest agent.</td></tr>
<tr><td>Design Schematic</td><td>Implementation</td><td>Alternative Options</td></tr>
<tr><td rowspan="4">See Figure 6-18</td><td rowspan="2">Initially, Interfaced with unaware agents.</td><td>Sequential: Agents become aware.</td></tr>
<tr><td>Integrated: Agents aware and now contributing to the spread of pollution.</td></tr>
<tr><td rowspan="2">Hybrid AB-SD [NetLogo (v4.0.3)]</td><td>ABS: yes – a static agent class could represent patches and pollution spread.</td></tr>
<tr><td>SD: possibly at first – use agent-oriented SD design to include local measures of pollution and population risk. Proposed extension to modify agent behaviour based on local conditions down to one-to-one contact in both time and space may be challenging in SD.</td></tr>
</table>

This formal representation of the conceptual model provides a clear summary of the model design and prompts for alternative modelling options to be considered. Whilst it may be possible to build this model in either a SD or ABS only paradigm, the objective of this study explicitly requires the use of the hybrid AB-SD combination. In cases where the modelling objective does not explicitly direct a specific modelling approach, then consideration of alternative modelling options at this stage might provide a useful review before committing to model implementation.

6.2.5 The Interfaced Model

In this model, the ABS and SD modules are progressed in single time steps with no interaction between modules. This is akin to a pollution event in which people or animals are unaware of prevailing contamination, for example. An agent is considered to be at risk when it is positioned on a patch where the absolute difference between the normal ('lime') colour setting and the actual colour of the patch is greater than a user-defined limit: defining each agent's risk factor. At each time step the percentage of loner and social agents at risk is calculated and presented as the output of the model; akin to looking at aggregate health risk in unaware populations. It would be possible to run the ABS and SD modules fully over the intended duration of a simulation. The output of each could then be used to generate the model output. The key factor in recognising this design class is that there is no interface between modules, yet the model output requires input from both.

The status of the ABS and SD modules are overlaid in Figure 6-10 at initiation and after 100 time steps (Simulation Time = 5) (social agents are red and loner agents are black throughout this case study; highlighted for reference in case this thesis is viewed in Black and White). In this example, 3 patches are set to 'sky', dt = 0.05 and delay1 = 30 in the SD module, 100 agents are used to represent each population type and the risk limit for agents is set to 5.

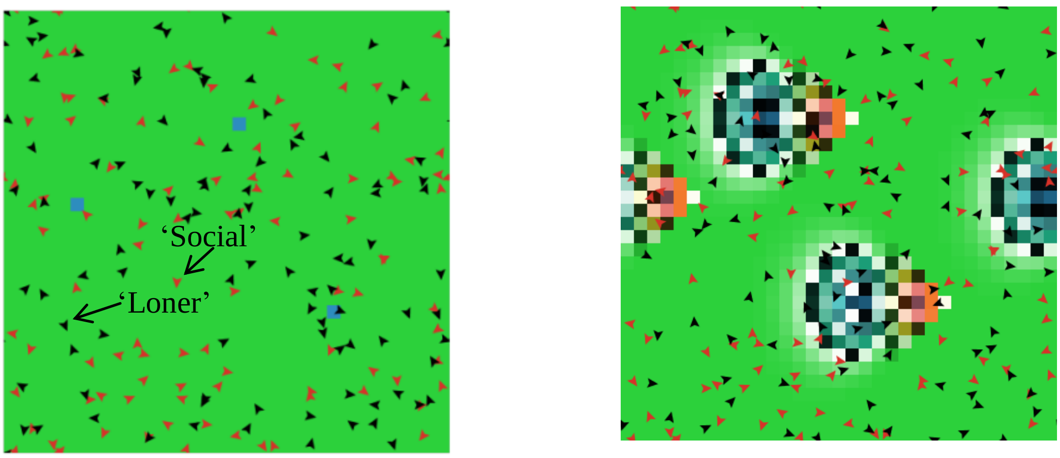

Figure 6-10: Module status (interfaced model) at initiation (left) and after 100 time steps (right)

Over the course of a simulation the percentage of each population exposed to risk can be plotted as shown in Figure 6-11 as an example output for this specific simulation run.

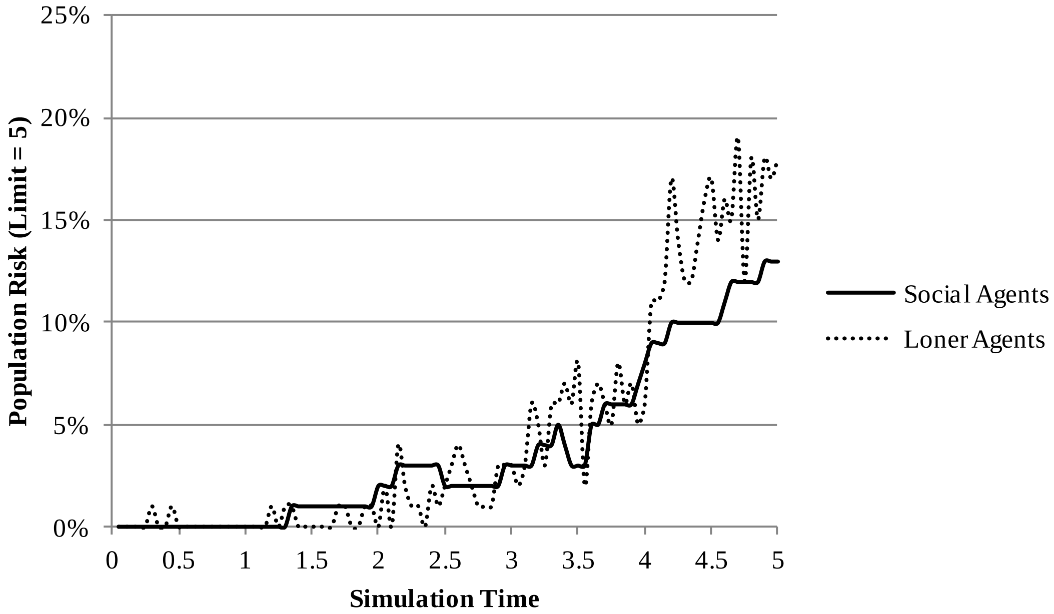

Figure 6-11: Example output from the interfaced model

In this case, the loner agents end up at greatest risk and the nature of their risk profile over time fluctuates more than that for social agents. Whilst analysis will not be extended further for this example, it would be possible to build a strategic profile of population risk using a simulation model such as this. Risk, as defined previously, could be investigated under a range of scenarios. This could include experimentation with population densities, agent behaviours and environmental conditions, for example.

6.2.6 The Sequential Model

In this model the agents were modified such that they could now observe the SD generated environment. As shown in Figure 6-12, agents now look to use patches that are as close to normal ('lime') as possible when moving. Even if they are stationary, being sufficiently far enough away or close enough to other agents depending on social preference, agents will look to move to a better (more normal) nearby patch.

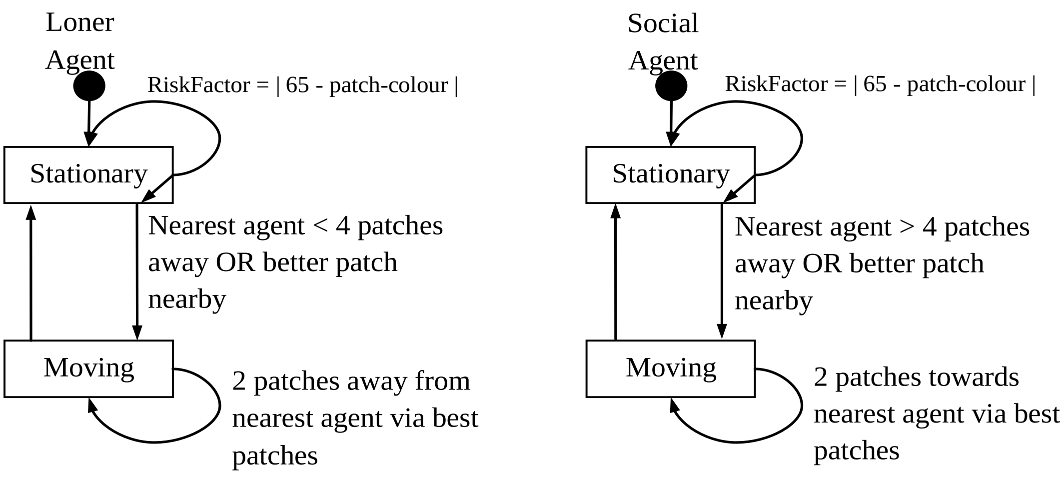

Figure 6-12: State diagrams for loner and social agents used within the sequential model

Agent movement was implemented using the Netlogo ‘in-cone’ utility which defines a vision distance and viewing angle centred on the direction in which an agent is facing. In this case a 90° viewing angle and vision distance of 3 patches was set in which the agent would move via patches that were closest to normal. Starting with the same initial conditions as for the interfaced model, the results of these modifications are illustrated in Figure 6-13. Agents have generally moved away from polluted areas and also social agents now tend to cluster together. As with the model implemented using the interfaced design class, the outputs of the modules in this model were combined to provide the model output at each time step. As with the interfaced model, it would also be possible to run each module through the whole simulation period and combine module outputs at the end in order to provide the model output. Again, it is the type of interface between modules that defines the design class, not the amount or nature of information passing from one module to another.

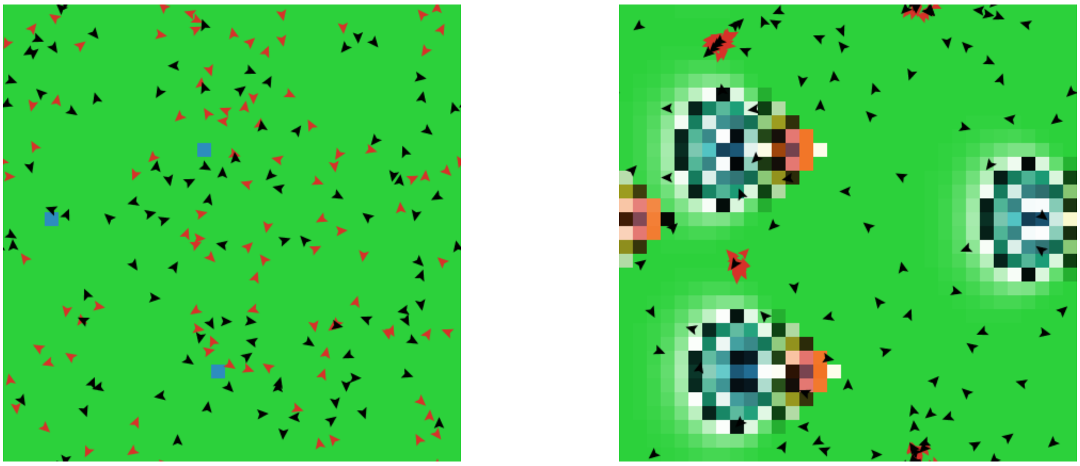

Figure 6-13: Module status (sequential model) at initiation (left) and after 100 time steps (right)

As shown in Figure 6-14 for this specific simulation, the aggregate impact of this modified behaviour for social agents is that their population risk remains very low. As might be anticipated, population risk for loners is also reduced compared to the results from the interfaced model, although the temporal variance in their risk appears to be consistent with that observed using the interfaced model.

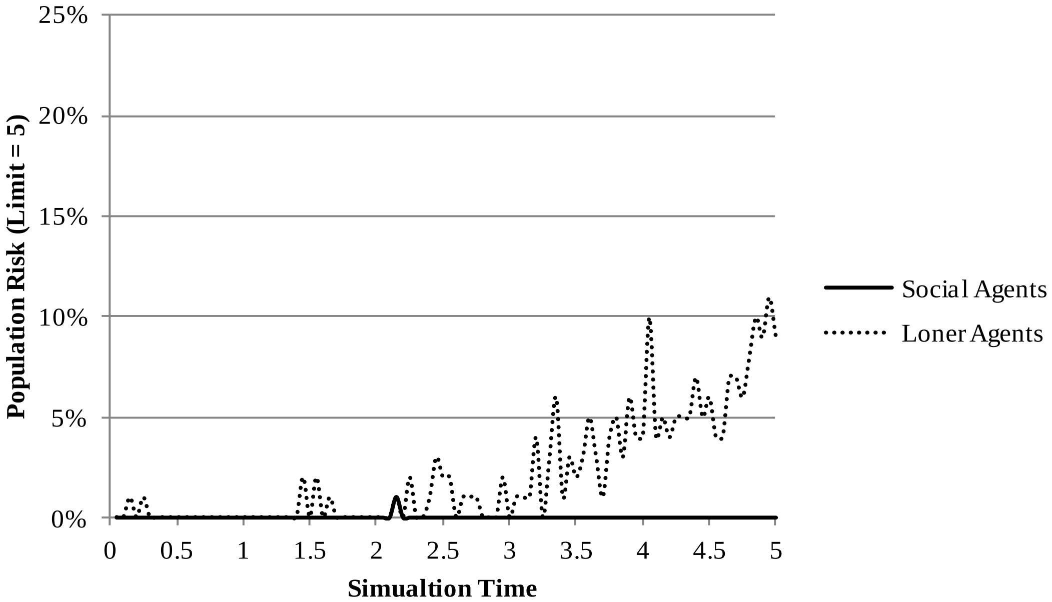

Figure 6-14: Example output from the Sequential model

6.2.7 The Integrated Model

Finally, the integrated model provides bi-directional feedback between the ABS and SD modules. Without changing movement rules, each agent is declared a hazard for all time once its risk factor exceeds the user-defined limit. For each movement thereafter, a hazardous agent changes the colour value of a patch it is occupying by an amount equal to its present risk factor. If close to zero then the occupied patch is set to near 'normal', but if the agent's risk factor is larger then it will influence the spread of pollution. The modified agent state diagram is illustrated in Figure 6-15. As a result of this modification, the SD module now propagates the impact of hazardous agents. Because of this feedback, however, it would not be possible to run each module independently as highlighted for the previous models; which are based on the interfaced and sequential design classes. At each time step, an agent may contribute to the spread of pollution and so the exchange of information between modules must be completed at each time step of the simulation.

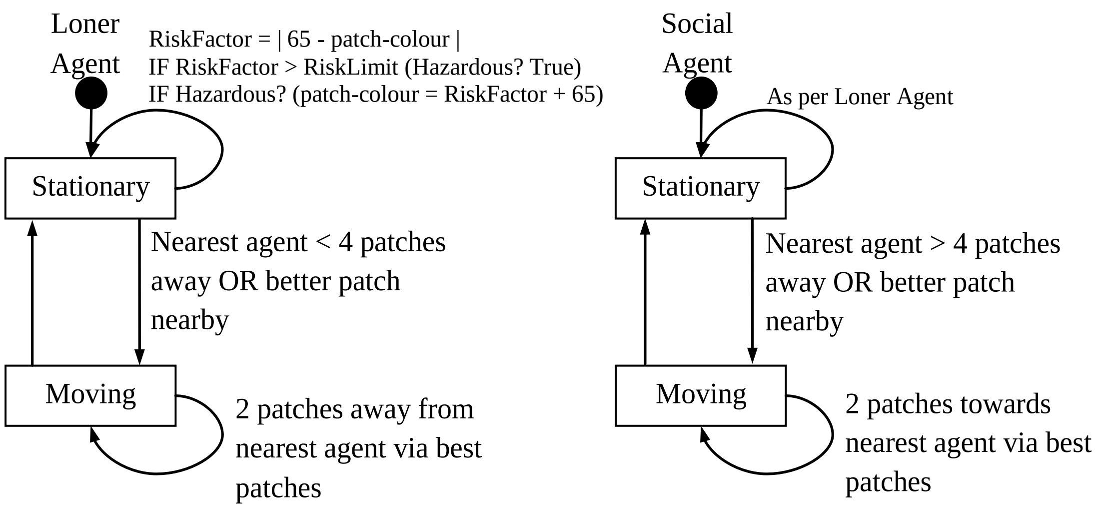

Figure 6-15: State diagrams for loner and social agents used within the integrated model

Again starting with the same initial conditions as previously, the results of this integrated model are presented in Figure 6-16 at initialisation (left), after ~75 time steps (Simulation Time = 3.75) (centre) and after 100 time steps (Simulation Time = 5) (right).

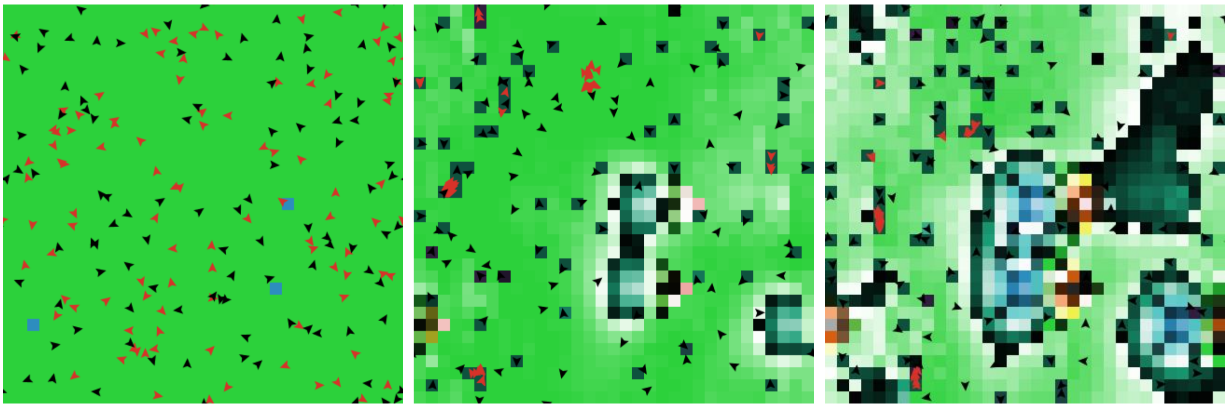

Figure 6-16: Module status (integrated model) at initiation (left), after ~75 time steps (centre), and after 100 time steps (right)

The influence of hazardous agents on the spread of pollution is clear, adding to the plumes that naturally spread from pollution sites. As shown in Figure 6-17, the social agent community is wholly at risk after 82 time steps. The rate of change in population risk differs depending upon social norms. This is due to the tendency for social agents to cluster, as is evident in the world-view after ~75 time steps, compared to the dispersed loner population.

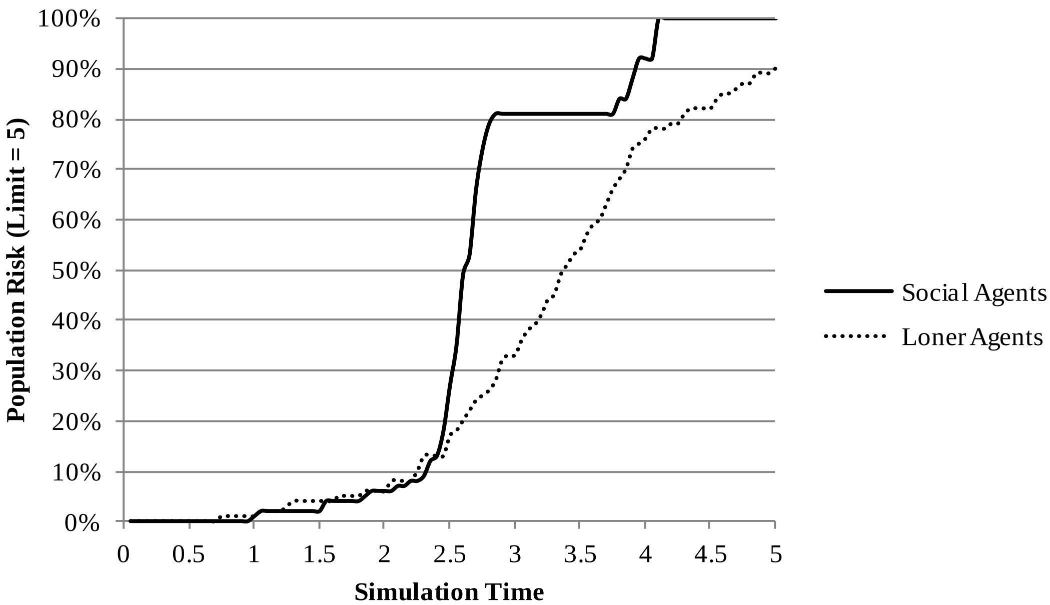

Figure 6-17: Example output from the integrated model

6.2.8 Architectural Review

Having described the implementation of three AB-SD hybrid models each designed according to one of the design classes defined by Swinerd and McNaught (2012a), a side-by-side review of the underlying architectures is next considered. Three basic forms of architectural representation are available for comparison. Firstly, the design classes as illustrated in Figure 6-1, secondly the general framework for capturing the content of conceptual models (Figure 6-3) and thirdly a schematic representation of model implementation. Through this comparison, Figure 6-18, the key differentiating factors for hybrid model design can be identified.

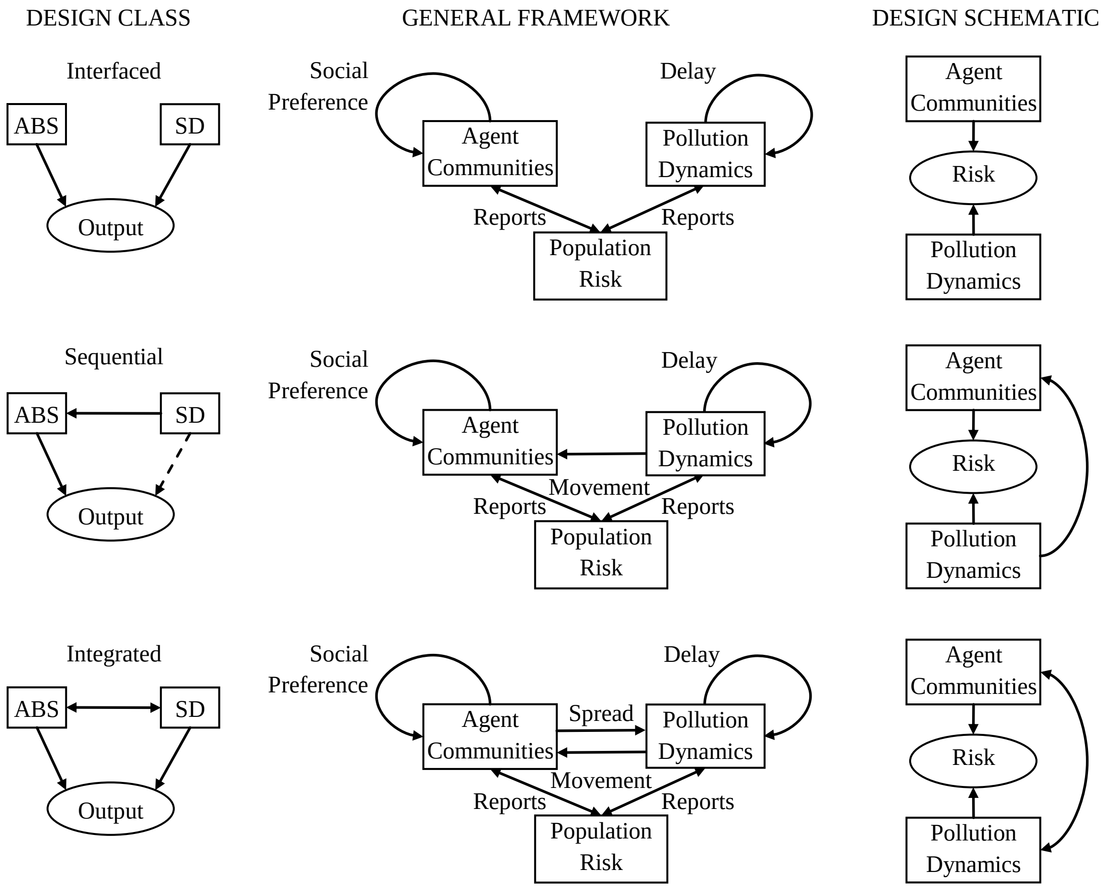

Figure 6-18: Side-by-side comparison of the architectural design of the three hybrid AB-SD models

In preparing to present the side-by-side comparison as described, careful thought was required when defining the 'environment'. Initially, the SD module might be considered as wholly representing the environment; however, the context of the case study, population risk, is only realised when the dynamics of the population are considered too. From an agent's perspective, the environment is a combination of known pollution and the relative location of other agents. In the interfaced model, agents are totally unaware of pollution; hence their environment comprises only the relative position of other agents, even though the output from the model combines both the spatial distribution of populations and emergent pollution conditions. When defining the 'environment' within the general framework, therefore, one has to consider both the 'individual' perspective and the context for modelling.

Even though the environment 'population risk' is dynamic, this is a 'zero' environment, as defined by Lorenz and Jost (2006), for all three models; i.e. modules do not interact with the environment beyond access to aggregate parameters. If, as suggested later in a proposed extension to the model, population risk is factored into individual behaviour, then the environment would be 'active' (as defined by Lorenz and Jost (2006)); agents would use information from the environment to shape their behaviour at each time step of the simulation. Having clarified the environment as representing population risk, i.e. the combination of population and pollution dynamics, the side-by-side comparison for the three models is readily made as presented in Figure 6-18.

Apart from the inclusion of more descriptive text, there is little difference between the representations of the design class and design schematic in this case. This is because of the relative simplicity of the models being analysed. Based on the results of the review summarised in Table 4-3, Chapter 4, and reported fully at Annex C, the design schematic can be relatively complex sufficient to mask the underlying design architecture. Recognising the differences in the interdependencies of modules in the design classes, most differences between the models can, in this case, be derived from the general framework.

In the case of the interfaced model, there is no relationship between individuals and observables and, therefore, there is no interface between agent communities and pollution dynamics for this model. For the model based on the sequential design class, the observable pollution dynamics characterise the behaviour of individuals, agent communities, because agents now look to avoid pollution wherever possible. In the integrated model, individuals are characterised by observables, i.e. agents look to avoid pollution, and the action of individuals affects observables, i.e. pollution is spread by hazardous agents.

Interfaces between the environment and both individuals and observables have bi-directional reporting. At the start of a simulation the number of pollution sites and agents in both populations is reported from the environment. During the simulation, the individual and observable elements respectively report individual risk and pollution spread to the environment.

Through the considered representation of design class, general framework and, to a lesser extent in this instance, design schematic, the principal contents, including interdependencies, of the three models have been formally identified. These representations provide a degree of clarity when looking to identify the differences between models, which can be most useful when comparing complex model implementations from different application areas such as demonstrated in Chapter 4. The choice of what design class to use will depend upon the objectives and context for a simulation study, but can be guided by the decision tree presented in Chapter 5. Regardless of which design class is selected, however, taking a methodical approach to model design facilitates planning for verification and validation of modules, their interactions and of the overall model.

6.2.9 Extending the Pollution Model

By using the representations of design architecture presented here, top-level opportunities for developing the model can be informed without ideas being obscured by detail. For example, the behaviour of aware agents could be modified as pollution spreads. Under these circumstances, an agent may prioritise personal risk reduction over social norms. This modification would require a change in how agent behaviour and interaction with the environment are represented. One approach would be to use another SD module implemented within each agent to determine the priority between social norms (i.e. being loners or social) and personal risk. This modification could be realised in a number of ways, one option providing opportunities for experimentation is presented in Figure 6-19. In introducing a risk calculation to agent behaviour based on information gleaned from the environment, the environment can be classified 'active' in accordance with that proposed by Lorenz and Jorst (2006).

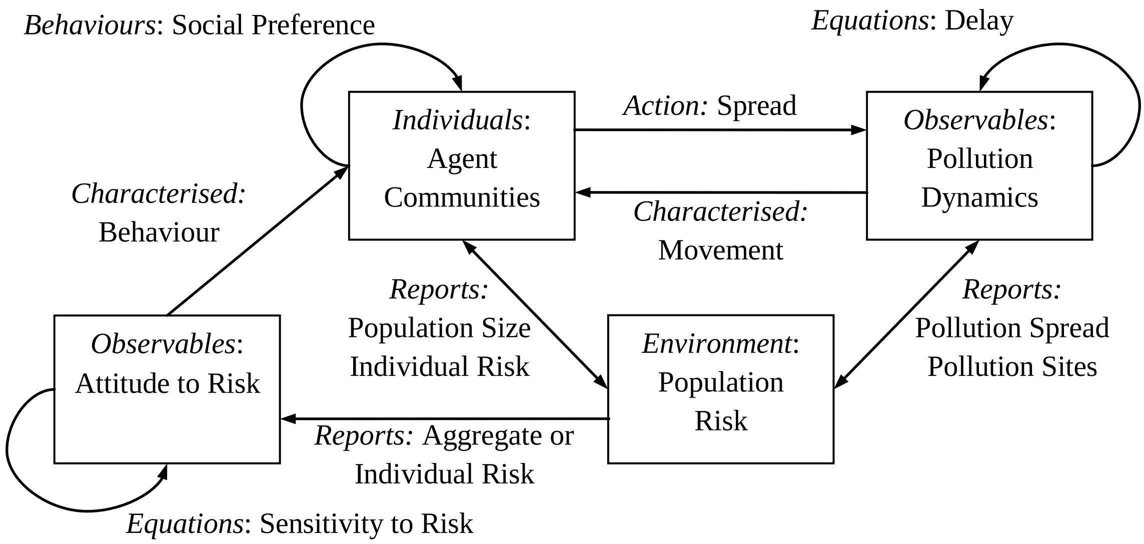

Figure 6-19: An example modification to the pollution model represented in the general framework

Experiments could be used to investigate the impact of information diffusion strategies amongst populations. Commonly reported information diffusion methods that could be explored are individual or broadcast communications such as achieved through word-of-mouth or the media, for example (Bass, 1969; Sterman, 2000; Swinerd, 2012). A model based on individual communications could exploit a reporting interface from the environment to the new module representing individual risk. The impact of broadcast communications could be represented through a reporting interface for aggregate risk. Alternatively, both local and broadcast communications could be represented and the relative impact of these on population risk explored. In all three cases, the equations balancing an agent's attitude to risk would be modified to represent their sensitivity to change in risk. This changing behaviour will ultimately characterise the movement patterns of the agent communities.

6.3 Benchmark Evaluations

The second part of this evaluation benchmarks this research against published articles that make observations on the initial guidance published by the author (Swinerd and McNaught, 2012a) and that report on design guidance for hybrid SD-DES modelling.

6.3.1 On the rigidity of the general framework and design classes

When considering a multi-method approach, some may consider that the prescribed design architectures described in Chapter 5 are too rigid: "… it would be naïve to assume that hybrid SD and ABM classes proposed by Swinerd and McNaught (2012a) exhaust all possibilities" - Balabam and Hester (2013, p. 1665), in consideration of the large scope for modelling social phenomena. However, these authors do not demonstrate any such limitation. Nonetheless, as well as reflecting on the benefits of adopting a structured design approach to hybrid modelling (for specification verification, reducing translation errors from conceptual modelling to model specification, for example) the versatility of using the general framework and design classes should be outlined.

Elements in the general framework can be either ‘individuals’ (I), ‘observables’ (O) or the environment (E). The environment reflects both the problem and the wider real-world context; it is not necessarily the output from a model. Individuals are discernable decision making entities such as individual people, organisations, nations or animals. Observables are described by equations such as natural processes or social, economic or political trends, for example. If present, the interface between ‘individuals’ is always of type ‘behaviour’ (B) and between ‘observables’ of type ‘equations’ (Q); i.e. these interfaces are described by behaviours or by equations, respectively. If present, the interface from ‘individuals’ to ‘observables’ is always of type ‘actions’ (A) and, vice-versa, always of type ‘characterised’ (C); i.e. these unidirectional interfaces are described by actions or by distinctive influential features, respectively. Any interface to the environment is of type ‘reports’ (R); i.e. reporting to or from each other. There can be any number of ‘individuals’ or ‘observables’, but only one representation of the ‘environment’ per model. If included, ‘individuals’ elements must always have an interface to the ‘environment’. These elements and associated interfaces define the proposed general framework as represented in Figure 6-20. In any subsequent model, all individuals and observables elements must directly or indirectly contribute to the output of the model. The environment element does not have to contribute directly to the model output.

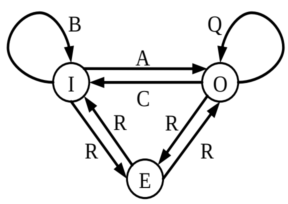

Figure 6-20: A concise representation of the general framework

Between elements (*n*) there are four possible combinations of interface; no interface (x), unidirectional interfaces in either direction (← or →), and unidirectional interfaces in both directions (⇆). For a given number of identified elements within the general framework and ignoring the looped behavioural and equation interfaces, it is possible to define the maximum number of framework configurations (c_{max}) as: $c_{max} = 4^{n\frac{(n-1)}{2}}$.

So, for *n*=2, the four possible framework configurations (where a circle represents an element of the general framework) are:

Figure 6-21: Possible framework configurations for 2 elements

With *n*=3, the 64 possible framework configurations are:

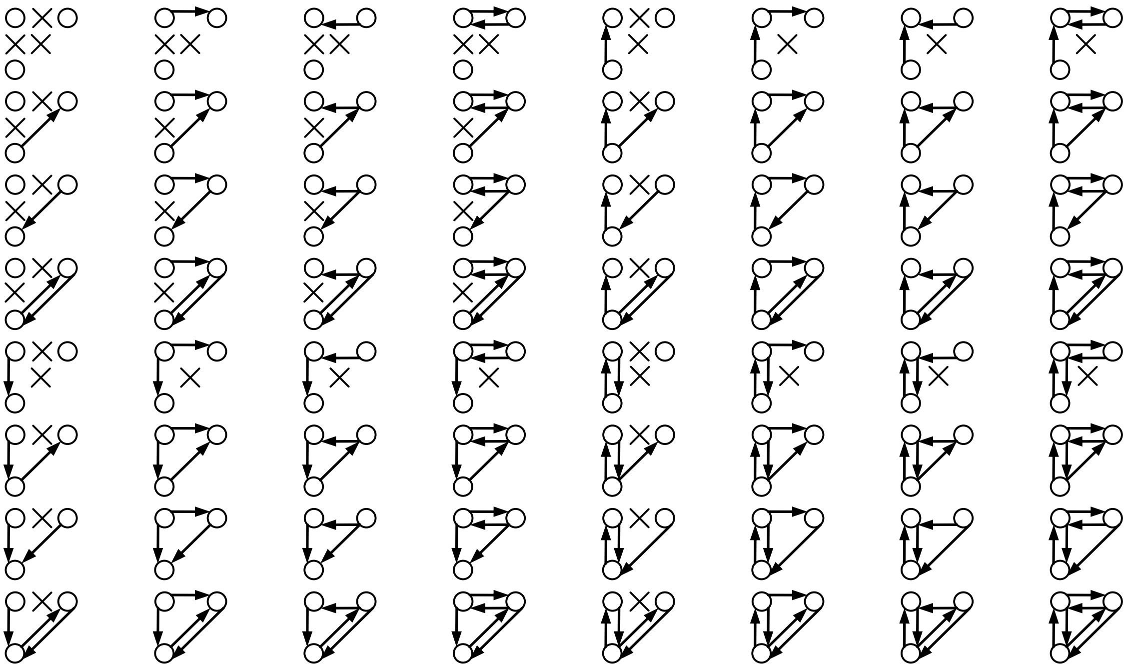

Figure 6-22: Possible framework configurations for 3 elements

With *n*=4 the possible number of configurations grows to 4096 and for *n*=5 to 1048576, and so on. It is, therefore, proposed that whilst the general framework and design classes combine to provide a structured approach to the design transition, they do not limit the scope for creative design.

6.3.2 Comparing the general approach of Chahal, Eldabi, and Young (2013)

Building on the specific comparison presented in sub-section 6.1 to Chahal, Eldabi and Young's (2013) conceptual framework and evaluation criteria for design guidance, this comparison considers the general approach.

Their method validates that used for this thesis, i.e. they reviewed reported hybrid models to derive their general guidance (for SD-DES hybrid models). They subsequently propose a 'conceptual framework' to represent the entire decision making process when looking to use hybrid SD-DES models. The stated practical and social implications of their research align to the aspirations of this thesis (Chahal, Eldabi, and Young, 2013 p. 50): "… [to] *aid in the development of hybrid models capable of comprehending both detail as well as dynamic complexity, which will contribute towards a deeper understanding of the problems, resulting in more effective decision making*." And: "… *encourage those engaged in simulation (e.g. researchers, practitioners, decision makers) to realise the potential of cross-fertilisation of the two simulation paradigms*."

Their comments on model complexity reflect that reported by Swinerd and McNaught (2012a p. 118) who comment: "*The complex, multi-faceted nature of many modern-day systems can pose considerable challenges for traditional, single-methodology simulation approaches. While these challenges are often successfully overcome, they may stretch the methodology and call for considerable ingenuity on the part of the modeller. In such cases, it may be that an alternative hybrid simulation approach, either using another modelling paradigm or a hybrid approach, could provide a simpler, more natural or more efficient solution*." Chahal, Eldabi, and Young (2013 p. 51) state that: "*One of the main reasons behind using hybrid models is to reduce complexity (Antsaklis and Koutsoukos, 1998). The extensions of a paradigm to include the behaviour of another paradigm increases complexity. It has been argued in literature that a hybrid approach, wherein SD and DES are integrated* *symbiotically, will provide a more realistic picture of complex systems with fewer assumptions and less complexity (Chahal and Eldabi, 2008b; Brailsford, et al., 2003)*." Whilst their argument about fewer assumptions may be challenged (a model is always a simpler description of the real-world problem and so the conceptual model will be a simplification based on assumptions; see Figure 2-2), their argument with respect to model complexity is consistent with that of this author.

Their conceptual framework builds on three requirements drawn from a literature review (Chahal, Eldabi, and Young, 2013 p. 51): 1) The nature of information being exchanged [between modules]; 2) how such information is modelled; and 3) the nature of the interaction [between modules through exchange]. They do not detail the extent of their literature review in the paper. Whilst not explicitly stated, it is likely that their conceptual framework aligns to the design transition as defined in this thesis. They report (p. 53): "*The frameworks developed in the past have emphasised more on technical automation of exchange of information between SD and DES rather than providing generic guidance for implementation of hybrid simulation. Due to the inherent challenges associated with mixing models, generic conceptual frameworks should precede technical architectures (Mingers, 2003)*." They also state (p. 56): "*Without understanding the problem, it is difficult to develop an appropriate model*." Although they show their framework starting at 'start', it might be more useful to represent their framework within the general modelling process; most likely between conceptual modelling and model specification as presented here.

Whilst not formally linked to software engineering standards, their mapping (p. 59) of SD and DES models (modules) strongly reflects such guidance. The author reflects that it must be rare for simulation research papers to formally cite software engineering research standards; no examples have been found in the literature reviewed in support of this thesis, for example.

With respect to the formal integration and interfacing of modules, there is good agreement between that reported in this thesis and that described by Chahal, Eldabi, and Young (2013, p. 54): "*As all interactions between SD and DES models occur through specific points/variables, it is important that the framework provides explicit guidance for identifying such interaction points*." They define different types of 'interaction points', i.e. interface relationships between modules: 1) direct replacement where a variable in one module directly replaces a variable in another module; 2) aggregation/disaggregation where a variable in one module is represented in another module through aggregation (i.e. AB to SD module) or disaggregation (i.e. SD to AB module) as appropriate; and 3) causal where the value of a variable in one module influences the value of a variable in another module. These descriptions supplement the research presented here on design classes and concepts and further research should be undertaken to explore this.

Chahal, Eldabi, and Young (2013) reflect on the need to understand both problem and system contexts (p. 57) which aligns with Robinson's guidance (2011, 2012) and which is represented in this thesis through the use of the 'V' life cycle model. Their useful Venn diagram fit (p. 58) between "problem, system and methodology" and discussions on selection criteria for modelling paradigms also warrants further investigation in conjunction with this thesis.

Based on their review of SD-DES and this thesis for AB-SD hybrid combinations, there is much agreement. Whilst there are subtle differences between the two and some disagreement with respect to the extent of available design classes, there is sufficient common ground to suggest that generic design guidance could potentially be extended across the SD-ABS-DES paradigm mix.

6.4 Chapter Summary

Bringing together the guidance on hybrid AB-SD simulation model design developed in previous chapters, this chapter has used a simple abstract case study to:

- Successfully demonstrate the implementation of all three design classes for hybrid modelling using the AB-SD modelling combination.
- Formally present the conceptual model for the case study, provide a review of architectural design by comparing models using the general framework, and represent the selection criteria for utilising each of the hybrid design classes through the decision process.
- Indicate the flexibility of the general design guidance for coherently extending the complexity of model design.

The benchmark comparison with other published research indicates that:

- Whilst the general framework and design classes are structured with associated rules, they do not limit the scope for design or creatively as postulated by Balabam and Hester (2013).
- The time dependency of information exchange between modules shown to differentiate interfaced and sequential designs from integrated designs agrees with the definition of cyclic and parallel interactions described by Chahal, Eldabi and Young (2013).
- Contrary to that reported by Chahal, Eldabi and Young (2013) on the basis of the observations of Fairley (1976) and Lee, et al. (2002), modules that are implemented in different modelling paradigms but not directly interfaced can be used as part of a valid hybrid design, where the output of the model is dependent upon contributions from both modules.

Chapter 7 CONCLUSIONS

7.1 Review

The aim of this research was to develop methodological design guidance for hybrid simulation models that combine ABS and SD. This modelling combination was chosen as it is the least well researched hybrid compared to other combinations, yet it is currently generating the greatest level of interest with research publication rates outstripping any other combination: a likely reflection on the potential offered by this pairing to better model modern complex adaptive systems found in the real-world.

Noting the lack of published guidance for methodological design, the first research objective was to determine where in the general modelling process this research gap is. Having identified the design transition, the next research objective was to precisely define that transition in order that a critical and focused review of the published literature could be undertaken. Whilst unsurprising, given that design is fundamental to the general modelling process, it was found that the design transition is often reported but that this reporting is inconsistent and, often, incomplete. Hence, it is difficult to draw general guidance for best practice with which to shape future designs, identifying the research gap for this thesis.

The next research objective was to consider how to address this gap in the knowledge. A two-fold methodological approach was defined, taking advantage of the fact that much useful information is available in the published literature. This inductive research approach required systematic methods for capturing information in the literature in a consistent manner whilst also drawing across a wide range of application domains in an attempt to realise guidance that could be generally applied. Firstly, a method for capturing the content of conceptual models was developed and applied to a diverse set of published literature. Drawing on the findings of the initial literature review, only research publications that reported the implementation of hybrid AB-SD models were considered as these were considered to be the most relevant sources for information extraction. In the next phase of analysis, a review of the underlying architectural design of models was conducted and successfully mapped to three defined archetypes. In completing these analyses, a decision process for selecting design classes for hybrid AB-SD models was realised.

The evaluation of this research was achieved both by demonstrating the application of the guidance through a case study and by benchmarking the findings arising from this research with results and commentary from other research sources. The comparison with the findings of Chahal, Eldabi and Young (2013) serves to validate the research approach reported here and also demonstrates good agreement between the guidance derived here for hybrid AB-SD models and, in their case, hybrid SD-DES models. The agreement is sufficient to warrant further research to explore the potential for extending design guidance to cover any combination of ABS, SD or DES modelling. The response to Balabam and Hester (2013), serves as a useful demonstration of the versatility of the guidance proposed here; a versatility that allows a mix of scientific and artistic contributions to the design transition.

Whilst not reported in detail in the thesis, this research was informed by my own building of hybrid AB-SD models, which have been reported separately in the peer reviewed literature (Swinerd and McNaught, 2012a; 2014; n.d.) and at conferences (Swinerd, 2012; Swinerd and McNaught, 2012b).

The general contribution made by this thesis to the scientific field of modelling and simulation is the evidence-based formulation of guidance for the design of hybrid models that use the AB-SD modelling combination. Within this general theme, specific contributions presented in this thesis are:

- Chapter 2– Formal definition of the design transition using a systems engineering method (see Figure 2-8);

- Chapter 4 – A general framework for capturing the content of conceptual models (see Figure 4-3);
- Chapter 5 – The definition of design classes for AB-SD hybrid models (see Figure 5-3);
- Chapter 5 – Illustrations of design concepts (see Figures 5-4, 5-5 and 5-6);
- Chapter 5 – The decision flowchart to aid in the selection of a hybrid AB-SD model class (see Figure 5-9); and
- Chapter 6 – The implementation of three hybrid AB-SD model variants designed to demonstrate the differences between the three identified hybrid design classes.

7.2 Reflection

In order to develop this thesis, much time was spent building hybrid AB-SD models in one form or another. The aim was to build at least one credible hybrid model: credibility being measured through peer review acceptance in an applied research domain. In meeting this credibility metric, the author believed it would also serve to bring credibility to this thesis for developing general guidance. The published example of these efforts is the hybrid AB-SD model of international diffusion of technological innovation (Swinerd, 2012; Swinerd and McNaught, 2014). Whilst the model itself is relatively simple, much time and effort went into sourcing auditable input data, model verification and validation, configuring the model (using an evolutionary programming technique (Swinerd and McNaught, 2012b)) and describing the model. The guidance developed in this thesis was in various stages of maturation during this period. Whilst this model is not specifically reported in this thesis, the lessons learnt are captured and represented.

On reflection, this was a necessary investment as it gave first-hand experience of the challenges of deriving model design, gaining acceptance of a model and, importantly, acceptance of the output from the model. It certainly highlighted the rate at which model complexity can grow leading to significant computation time; especially with respect to ABS. However, it is also clear that in applying the model to a well-established research domain, such as diffusion of innovation, that the focus can shift from the author's primary intent, that of model design, to the applied subject area itself. In order to redress this, the relatively simple and abstract case study presented in this thesis more usefully serves the intended purpose: to demonstrate different design classes for hybrid AB-SD models. Coming up with a simple and abstract model, however, was incredibly challenging. Certainly, students of simulation should start early in their research to develop conceptual modelling ideas as it may take quite some time to settle on and mature an appropriate concept.

In terms of generating the guidance derived, it is proposed that the continual critical review of published literature during the course of this research was a valid method. On reflection, it would have been better to capture the views of the modellers themselves as this would reduce the chances of misinterpretation of that reported. In order to mitigate this limitation, that inferred by the author is presented at Annex C and the literature included draws from a diverse range of application areas. Editorial limits establish page limits to journal and conference papers, which, depending on the intention of the author(s), may reduce the scope for describing early design choices. Having said that, it has been found in the literature reviewed that, when described, model design is mostly presented through diagrams; which is an efficient method. Authors may then wish to consider using the general framework for representing the content of the conceptual model presented in this thesis as a means for efficiently presenting model design in published work.

Whilst formal methods drawn from systems engineering and software engineering have been used to underpin this research, the author has not explored the potential contribution that computer science might make. Given the established research disciplines of modelling and simulation, computer science, software engineering and, to a lesser degree, systems engineering all share common ties with computer technology and managing complexity, it is somewhat surprising to the author that such links have not surfaced during the course of this research. This may in part be due to my focus on applied research in the literature rather than the purely theoretical.

7.3 Further Research

Whilst the primary focus for this thesis has been to develop guidance for the design of hybrid AB-SD computer models, a number of opportunities for further research have surfaced along the way. In particular, some opportunities include: extending guidance beyond the AB-SD modelling combination, developing the dynamic hybrid design concept (see Annex D for initial ideas), and translating design guidance into modelling tools.

Abridging the research of Chahal, Eldabi, and Young (2013) with that reported here provides a basis for exploring whether general design guidance can be extended beyond the AB-SD or SD-DES modelling combination. There are published examples of other combinations such as: finite-state-machines (FSM) with SD (Levin and Levin, 2003), decision analysis (Bayesian Networks) with SD (McNaught, 2003), CA with ABS (Han et al., 2009), CA with Markov Chain modelling (Lauf et al., 2012), or CA with SD (Meng and Chen, 2012 cited by Sohl and Claggett, 2013), for example. Can the guidance described in this thesis be demonstrably applied to other combinations? If so, are there any preconditions, etc?

Even though hybrid modelling can be used to reduce model complexity when representing a real-world problem, there may be occasions when the nature of the problem changes such that a different modelling approach may more efficiently complete a simulation. The concept of a dynamically changing model may have utility. A few initial ideas are expanded upon at Annex D covering event or time reconfiguration of a hybrid model and structural reconfiguration of SD models using ‘agent flows’ that can dynamically change the flows between SD stocks.

A third avenue for further research is to investigate the potential for incorporating design guidance into modelling tools. Looking to both enhance and facilitate efficiencies in the design process, model vendors may be interested in exploring this opportunity. Such integration within modelling tools could be linked to verification and validation and supplement facilities for sensitivity analysis. Techniques for auto-translation of ABS are published, but, for example, can such processes be extended to hybrid model design?

7.4 In Closing

This research shows that fundamental design choices for hybrid AB-SD models are relevant to a wide range of application areas. Exposing these design choices before moving into technical specification and model implementation reveals opportunities for more efficient model design to decision makers and to academics, practitioners and students of modelling and simulation. Some may argue that the focus on hybrid modelling can overly complicate a model and detract from the task at hand, to inform decisions about a specific real-world problem. However, as Lane (1994) suggests, it is surely better to have available a range of approaches and tools for simulating real-world problems in support of decision making.

This thesis contributes to the scientific field of computer modelling and simulation by considering in detail the design of the emerging category of hybrid simulation models that combines agent-based simulation and system dynamics. This contribution has been made using an inductive research approach, using observations of the published literature to describe the underlying design transition. In order to identify when a hybrid AB-SD approach may be suitable and, if so, what type, a general decision process has been proposed. The resulting general guidance is demonstrated through a case study using different design archetypes. It is hoped that this research contribution will be used by others to enhance the design transition of their modelling process when using hybrid simulations and, hence, enhance their ultimate support to decision making.

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Annex A – Summary of Computer Modelling Paradigms and Tools

A-1 Background

The simulation of real-life systems using computer models is a long-established practice (e.g. Forrester, 1961 and Tocher, 1963), conducted in a number of modelling paradigms and applied to a diverse range of applications. Indeed, this thesis cites examples of computer model design from applications as diverse as land change science, workforce planning, technology adoption, supply chain dynamics, and pension fund governance.

Models have, in fact, been used for hundreds of years, starting with verbal, drawn and physical models and moving towards mathematical and analytic models. It is debatable whether the design of models is more a science or an art, but most would agree that it involves some combination of the two. As discussed by Bonabeau (2002, p. 7287) with respect to agent-based modelling: "The model has to be built at the right level of description, with just the right amount of detail to serve its purpose; this remains an art more than a science." Nonetheless, in order to maximise the potential of a model to facilitate simulations of the real-world, the modeller needs appropriate tools for model building: recognising and applying appropriate tools is a skill that combines knowledge with experience. As the carpenter learns what hand tools suit particular woods for different components of a true-scale physical model, so the computer modeller also needs to recognise the advantages and disadvantages of modelling paradigms and techniques for applied simulation. Described by Homer and Oliva (2001, p. 351), simulation facilitates the isolation of the core structure underlying a problem behaviour; for which using an appropriate model is essential. This is demonstrated by Holland's observation with respect to using different modelling paradigms to analyse the same problem. He states (1999 cited in Scholl 2001b, p. 14): "interdisciplinary comparisons allow us to differentiate the incidental from the essential. When we look for the same phenomena in different contexts, we can separate features that are always present from features that are tied to context."

With the advent of the computer and computer modelling, came the need to develop associated skills built on established branches of science, engineering and mathematics. These skills are now taught within disciplines such as operational research, management science, computer science, systems engineering and software engineering. There are many modelling paradigms, but of particular interest here are those designed to isolate the dynamic behaviour of systems. As Homer and Oliva (2001, p. 349) state: "Simulation modeling provides a tool for formally testing the dynamic hypothesis and determining its adequacy." [sic] They also state that qualitative, soft, techniques can be used to capture system structure but not the dynamic behaviour of a system. They cite Sterman's view (Homer and Oliva, 2001, p. 349) in this respect: "Experimental studies have shown repeatedly that people do a poor job of mental simulation even when they have complete knowledge of system structure and even when that structure is quite simple."

Simulation modelling paradigms essentially provide either a 'bottom-up' or 'top-down' approach relative to the dynamic behaviour of interest. In the 'bottom-up' approach, a system is simulated at a level of abstraction below that of the dynamic behaviour of interest whereas, in the 'top-down' approach, dynamic behaviour is represented by simulating system structures at a level of abstraction above that of the dynamic behaviour of interest. Both approaches have been usefully applied across many domains. In recent years, there has been increasing interest and debate about the potential of hybrid approaches that combine somehow the 'top-down' and 'bottom-up' methodologies. This interest is driven primarily as this approach may facilitate more accurate representation of modern real-world systems capturing behaviours not well represented by any one modelling paradigm (Lane 1994; Phelan, 1999).

A-2 System Dynamics Modelling

System dynamics (SD) has a well documented history since its inception in the 1950s by J Forrester when he was working at the Massachusetts Institute of Technology. Making the link from control theory, within an electrical engineering context, to applications in management and business contexts provided the fledgling field of management science a formal basis against which models could readily be verified and subsequently validated. As such, it was possible to build credibility in this process for informing management action. The underlying concept of feedback and its implications for industrial dynamics, the title of Forrester's seminal book on the subject (Forrester, 1961), provide explicit insight into causal decision making, dynamic processes and policy analysis.

Representing the resources and dynamics within a system as a set of stocks and the flows between them, SD captures feedback and delay processes to model system behaviour over time. The stocks provide aggregate representations of entities within a system, with flows in and out of them regulated by feedback and delay such that resultant system performance can be non-linear and, indeed, sometimes counter-intuitive. Resource flows correspond to the mean rates at which entities within the system change state.

SD models can be directly mapped to causal diagrams which show the structural relationships between principal factors to be included within the model. This is a significant strength of system dynamics, as causal diagrams can be used by all interested parties to collectively agree, or openly disagree on, the structure of the problem; a common modelling source of simulation error (Robinson, 1999). By forming a consensus of what is in and what is out of the model and by agreeing what is linked and the nature of those links, the structure of the model has meaning and relevance. Within the context of the agreed structure, 'what if' scenarios can be played out to determine the implications of decisions, processes or policies before they are committed to or retrospectively in order to analyse why issues are arising. In a sense, the agreed model of system structure is ‘fixed’, a feature that is contrasted with the other modelling paradigms later.

A potential limitation with SD arises when the mathematical representation of a system component is not well defined. In such cases, table functions or random-numbers are often implemented but without formal explanation. This can limit buy-in to the model and hence its credibility. An example overcoming this is provided by Homer (1999) who used an AB model to generate a table function in an SD model. Use of the AB model gained buy-in and, subsequently, the table function was given credence within the SD model.

It is because system dynamics models are structured in this manner, that the term top-down has been used to describe the approach. This reflects the fact that system dynamics models are constructed at a level of abstraction higher than the level at which a decision or insight is required. For example, a model of a supply chain whose purpose is to identify inefficiencies in the underlying performance of that supply chain. Experimental design when using a system dynamics model will typically test different strategies through the structure and rates of the model, observing the impact on stocks as a function of continuous time.

A-3 Agent-based Simulation Modelling (and Cellular Automata)

Compared to system dynamics and discrete-event simulation, agent-based modelling is a relative newcomer. Its development has been facilitated by the advent of object-orientated programming and use of asynchronous programming techniques. Agent-based modelling, in common with cellular automata modelling, focuses on individual entities; a ‘bottom-up’ approach.

The phrases ‘top-down’ and ‘bottom-up’, sometimes referred to as deductive and inductive respectively, have been used by a number of authors to represent the underlying design philosophy for computer models (Schieritz and Milling, 2003; Scholl and Phelan, 2004; and Verburg and Overmars, 2009). Whilst these phrases have been used in other application areas also to represent methodological approaches, examples of their use in describing computer modelling date to the 1980s. For example, Higgs, Parmenter and Rimmer (1983, 1988) discuss a hybrid top-down, bottom-up approach to provide information about the effects of national policy at a State level within a Federal economic system. They outline the benefits of adopting this hybrid approach to overcome both the theoretical shortcomings of a previous top-down, economy-wide model whilst reducing the data and computational demands of a wholly bottom-up approach.

Cellular automata models are used to represent the state of individual cells within a grid of cells. The state of a cell can be influenced by the state of neighbouring cells and thus local emergent conditions can arise, which gives rise to an explicit spatial context in modelling output. As with agent-based modelling, this paradigm provides a bottom-up approach to system modelling whereby emergent outcomes are observed at a level of abstraction higher than the entities represented in the model (in direct contrast to the SD approach). A classic example of cellular automata modelling is Conway’s Game of Life which became widely reported on during the 1970s and is still the subject of published research; see Holland for an overview of cellular automata in the context of constrained generating procedures in which Conway’s Life automaton is used as an example (Holland, 1998, pp. 125-142).

Object orientated programming provides the opportunity to formally declare individual properties of entities, (agents), within a framework for data acquisition, processing and sharing. The question of what constitutes an agent has, however, been the subject of a number of published research articles. Looking to assess the integration potential between system dynamics and agent-based modelling, Schieritz and Milling (2003, p. 4) provide a wide ranging review of what constitutes an agent and introduce the concept of a 'continuum of agency'.

They introduce a table, replicated here at Table A-1, that summarises their literature review for terms that describe agent properties. They propose that there are degrees of agency exhibited in studies whereby an 'agent' will have a range of these properties; leading to the continuum analogy. Rocha's initial observation from his own review of what constitutes an agent suggests (1999 p. 3 cited in Schieritz and Milling, 2003): "definitions range from a mere subroutine to a conscious entity." In turn, Rocha highlights Holland's (1995 cited in Rocha 1999 p. 4) definition of agents as: "rule-based input-output elements whose rules can adapt to an environment." Rocha concludes from his own review (Rocha, 1999, pp. 24-25) that the fundamental requirements for semiotic agents are: asynchronous behaviour; situated communications; shared and cultural nature of language and knowledge; capacity to evaluate the current status; and stable decoupled memory. To the author's knowledge, there is no formally agreed definition of what constitutes an agent (Macal and North, 2006) and, therefore, that defined in Table A-1 will be used as a point of reference for this research. The cited examples from Holland and Rocha serve to illustrate the differences in reported descriptions, but these are captured within Schieritz and Milling's (2003, p. 5) properties of agents.

Table A- 1: Properties of agents; taken from Schieritz and Milling (2003)

Properties	Description
Proactiveness, Purposefulness	Ability to take the initiative in order to achieve goals
Situatedness	Embedded in an environment and senses and acts on it
Reactiveness, Responsiveness	Ability to react in a timely fashion to changes in the environment
Autonomy	Ability to control own actions and internal state
Social Ability	Ability to interact and communicate with other agents and sometimes have awareness of other agents
Anthromorphity	Having human-like attributes, e.g. beliefs and intentions
Learning	Ability to increase performance over time based on experience
Continuity	Temporally continuous running process
Mobility	Ability to move around simulated physical space
Specific Purpose	Design to accomplish well-defined tasks

An important construct of agent-based modelling is the relationships of agents with other agents and with the environment; noting it is possible that the environment can be defined by the agents themselves. As with cellular automata, local conditions can give rise to local emergent behaviour from which a spatial context for emergence can be demonstrated.

Agent-based modelling has been used in many research domains. Example application areas are social health (Viana, et al., 2012), microbiology (Wakeland, et al., 2004), and crowd dynamics (Heliövaara, et al., 2012). With the availability of increasing computational power, the number of agents and the complexity of their behaviour rules have also grown. This, however, can lead to a rapid increase in model complexity (Marin, et al., 2006; Rahmandad and Sterman, 2008, p. 999) hindering the model verification and validation process. Again, drawing from advances in computer science, computer graphics is increasingly playing a prominent role in systems modelling and especially agent-based modelling (Richmond, et al., 2010; Richmond and Romano, 2011). As well as assisting the validation process, this also enhances engagement with people involved in the development and use of models.

Whilst object-orientated programming provides a structured approach to coding models, there need be no fixed structure to the representation of the system being modelled using the agent-based approach. This is a clear distinction to system dynamics, where, as previously explained, the relationship between key system components are defined and ‘fixed’ for the duration of a simulation. This distinction captures the essence of the top-down versus bottom-up approach to modelling system complexity. Emergent behaviour of the system is observed at a level of abstraction higher than the entities within a ‘loosely-coupled’ agent-based model, whereas it is observed at or below the level of abstraction represented in a ‘fixed’ system dynamics model. Even though explicit societal links between agents are often used and reported, this concept of a ‘loosely-coupled’ representation is representative of the philosophy for this modelling approach, i.e. the representation of the system is not tightly bound, rather loosely bound by, often simple, governing rules.

Experimentation with agent-based models tends to focus on the guiding rules for agents, their interactions with each other, i.e. societal behaviour, and with the environment.

A-4 Discrete-event Simulation Modelling

As suggested by its name, this modelling approach explicitly represents the occurrence of discrete events within a system with most applications involving queuing systems in one form or another (Pidd, 2004). Different simulation strategies can be applied for evolving the system over time, (Behdani, 2012). Event-scheduling, or event-orientated modelling, focuses on serving the event list that represents the states of the system. In the activity scanning strategy, the focus for modelling are activities and their preconditions. In the process-interaction strategy, an entity is followed through the system, often represented in a process-view, where the entity passes through a number of steps drawing on resources and is subject to delay. The foci, therefore, when using DES are relationships between entities and associated resources relative to events, activities or processes.

As with agent-based modelling, discrete-event simulation is a bottom-up modelling technique. Typically, a process is modelled from which insights at a higher level of abstraction are realised such as support logistics, process efficiencies and resilience, for example. As with the other modelling paradigms discussed, DES has a wide range of applications. Pidd (2004, pp. 4-6) highlights a number of application areas for DES including manufacturing, transport, health care, and defence, for example. The general emphasis for experimentation explores dependencies between entities, resources and delays. Whilst the validation of discrete-event models can be achieved using classical mathematical methods, computer graphics are increasingly playing a role to help increase buy-in and represent the impact of the modelling process. The flow of entities and resources through a process over time is well suited to visualisation with computer generated graphics. Where a process such as in a manufacturing plant or warehouse already exists, computer-generated 3D visualisation can be used to provide a direct visual association between the model, modelling results and reality. Whilst discrete-event modelling is a bottom-up approach, it allows ‘fixed’ and ‘loosely-coupled’ system representation (as defined in the previous sub-section for ABS): for example, a fixed manufacturing process that is supported by entities that collectively can demonstrate emergent properties.

A-5 Modelling Tools

Tools have tended to be written for specific modelling paradigms leading to potential issues when looking to exploit a hybrid modelling approach; such as when interfacing different modelling tools (Gröβler, Stotz and Schieritz, 2003). However, with the growing trend to use hybrid models as illustrated in Table 1-1, tools have come to market produced explicitly to serve this need. The choice of modelling tool will be determined by a number of factors such as; previous experience, including the influence of learned institutions and personal bias, cost, licence conditions, the nature of the system being modelled and the needs of those involved, directly or indirectly, in the outcomes of the analysis of the system.

It is feasible that systems can be modelled using different approaches whilst achieving similar fidelity in experimental results. North and Macal (2009) used SD and ABS approaches to replicate the well-know Beer Game simulation and demonstrated equivalence in results to 12 decimal places. Earlier, Scholl and Phelan (2004) considered the use of these alternative approaches to triangulate and integrate understanding. Their reference to integration relates to the technique of looking at the same problem from opposite, top-down and bottom-up, perspectives in order to refine solutions. Macal (2010) later concludes that there are alternative approaches available to achieving the same results. The conclusions of Rahmandad and Sterman (2008, p. 1012) should, however, be considered in the context of: “robustness of policy choices to model assumptions.” As previously discussed, experience of the modeller and familiarity with alternative modelling paradigms are also factors (Morecroft and Robinson, 2005). Whilst one paradigm might be the ‘natural’ choice depending upon the system being modelled and the intended use of the model, the overall effort involved in ‘stretching’ a particular paradigm to represent key aspects of the system being modelled has to be balanced against the overall effort involved in employing a hybrid approach.

The output from a number of market surveys and comparisons of modelling tools (Sastry and Sterman, 1992; Borshchev and Filippov, 2004; Nikolai and Madey, 2009; Allan, 2010; Cimino, Longo and Mirabelli 2010; Roberts, 2011; Forrester Consulting, 2013; System Dynamics Society, 2013) have been amalgamated into Table A-2. For each entry, a web-based reference is provided, active at the time of writing, from which the reader may be able to gain further information or access to tools; these sources may not, however, reference the originators of the tools in every case. This summary is intended to represent the extent of modelling tools available beyond direct bespoke coding, it is not claimed to be exhaustive.

Table A- 2: A selection of modelling tools listed alphabetically by modelling paradigm

SD	ABS	DES
ASCEND (Carnegie Mellon University, 1978);	**ABLE**(IBM, 2004); **AgentBuilder® Lite/Pro**(Acronymics, Inc., 2004); **ADK**(Tryllian.com, 2013); **AgentSheets**(AgentSheets, Inc., 2012); **Ascape** (Source Forge, 2010)	**Arena®** (Rockwell Automation Inc., 2013); **AutoMod** (Applied Materials Inc., 2013)
AnyLogic® (The Anylogic Company, n.d.);		
DYNAMO; **dynsim**(Google Hosting, 2013) DYSMAP;	**Brahms**(Agent iSolutions, 2000); **Breve** (OpenGL (TM), 2008); **Cormas** (Cirad, 2001); **Cougaar**(Raytheon BBN Technologies, 2012);	**Plant Simulation** (incorporating **emPlant**) (Siemens Product Lifecycle Management Software Inc., 2013)
Forio Simulate™ (Forio Online Simulations, 2013); **iMODELER** (Consideo GmbH, 2013)	**ECHO** (Hraber & Fraser, 2002); **ECJ**(George Mason University, 2013); **FAMOJA** (University of Osnabrück USF Institute, 2007)	**Enterprise Dynamics** (INCONTROL Simulation Solutions, 2013); **ExtendSim** (Imagine That Inc., 2002); **FlexSim** (FlexSim Software Products Inc., 1993)
Insight Maker™ (Give Team, 2010)		
	JADE™(Telecom Italia SpA , 2013); **JAS**(Source Forge, 2004); **JASA**(Source Forge, 2002); **JCA-Sim** (Weimar, 2009); **jES** (Università degli Studi di Torino, 2013); **JESS**™(Sandia National Laboratories, 2012)	**GPSS/H, SLX** (Wolverine Software, 2007)
MapSim (Source Forge, 2009); **ModelMaker** (ModelKinetix, 2003)	**Madkit**(LIRMM, 2008); **MAGSY** (DFKI GmbH Saarbruecken, 2013); **MAML** (agent-lab.com, 1999); **Mason** (Georage Mason University and GMU Centre for Social Complexity, 2003); **Matlab** (The MathWorks, Inc., 1994); **MIMOSE** (University of Koblenz, 1999); **Moose** (University of Florida, CISE, 2013)	
NetLogo (Wilensky, 1999)		
STELLA®, **iTHINK®** (ISEE Systems, 1985); **Studio 9** (Powersim Software, 2013); **Simile** (Simulistics Ltd, 2002); **Sphinx SD Tools** (Source Forge, 2006); **Sysdea**™ (Strategy Dynamics Ltd, 2013); **SystemDynamics** (Source Forge, 2007); **TRUE** (TRUE-WORLD, 2002)	**omonia**(XLOG Technologies GmbH, 2005); **PS-i** (Source Forge, 2013a); **Repast and family** (Argonne National Laboratory, 2012) and (Source Forge, 2013b) **SDML** (Manchester Metropolitan University Business School, CFPM, 2013); **SeSAm** (SESAM, 2012); **SOAR** (University of Michigan, 2013); **StarLogo and family** (Massachusetts Institute of Technology, 2013); **Sugarscape** (Source Forge, 2013c); Swarm; **SimAgent** (The University of Birmingham, 2005); **SimBioSys** (McFadzean, 1994)	**ProModel** (ProModel Corp., 2013) **Simio** (Simio LLC, 2012); **SimProcess** (CACI, 1995); **SIMSCRIPT** (CACI Advanced Simulation Lab, 1995); **SimPy** (SimPy Developer Team, 2012) **Simul8** (Simul8 Corp., 2013);
VisSim (Visual Solutions, Inc., 2013); **Vensim®** (Ventana Systems Inc., 2012)	**VSEit** (Brassel, 2013)	**Witness** (Lanner Corp., 2008)

Whilst the modelling tools listed in Table A-2 are generally aligned to single modelling paradigms, some, such as Anylogic®, Netlogo and Insight Maker™ for example, are actually designed to support more than one paradigm.

Annex B – Netlogo

As indicated in Table A-2, Netlogo (Wilensky, 1999) is designed to provide both AB and SD modelling capability, although its primary focus is ABS. Freely available for academic use, it is used by tens of thousands of students, teachers and researchers worldwide (System Dynamics Society, 2013). A review of the Scopus® database for publications with 'Netlogo' in the title demonstrates ongoing use of this modelling tool with 28 listed since 2004 including contributions to peer-reviewed journals. With demonstrated application across a wide range of contemporary research areas from modelling mobile ad hoc networks to credit risk management, this tool appeared to be suitable.

In order to confirm the potential for representing hybrid AB-SD models within Netlogo, however, an SD model was replicated, in a manner similar to North and Macal (2009), based on Sterman's model of scientific revolution (Sterman, 1985). Not only was this work selected as it provided a detailed description of the model, which was implemented in DYNAMO, it also demonstrates an agent-oriented approach to SD modelling, which will be discussed more fully later.

Table B- 1: (Case Study) Modelling a theory of scientific revolutions (Sterman, 1985) in SD and ABS paradigms

As a scientific paradigm matures, puzzles arise that, without resolution, can be recognised as anomalies to the central theories on which the paradigm was established. The success of researchers working to solve puzzles increases the confidence held in the general belief that the paradigm is sound and hence can reinforce commitment to it: however, recognition of anomalies that bring into question the underlying theories, can reduce confidence in the paradigm. Change in confidence for a paradigm influences the amount of available research resource to it compared to other extant paradigms and also the proportions of research

resource assigned within it to anomaly and puzzle resolution. Confidence is also influenced by puzzle solving progress relative to other paradigms. The progress of solving puzzles is a function of available resource and the general level of difficulty of puzzles and anomalies; with anomalies being more difficult than puzzles. Paradigms, therefore, emerge and decay with differing rates and endure for differing lengths of time dependent upon confidence in the paradigm relative to other extant paradigms and especially the dominant scientific paradigm; Sterman (1985), Sterman and Wittenberg (1999).

Interpretations of the central constructs of this model are illustrated below to show puzzle solving and determination of confidence.

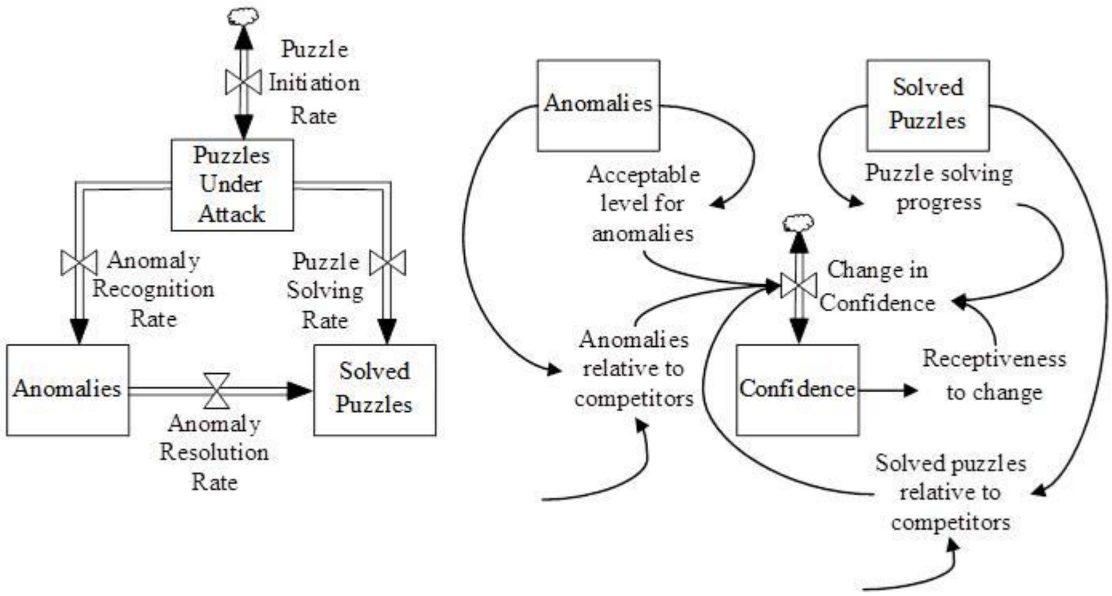


Figure B - 1: Summary of central design construct for a model of scientific revolution (Sterman and Wittenberg,1999) (reproduced with permission: Elsevier RightsLink® licence – 3263661433009)

In his 1985 publication, Sterman provides the DYNAMO code for his model. This was used to build an exact SD replica, as illustrated in Figure B-2, using the modelling tool Vensim® (PLE Version 5.7a). Whilst a full description of abbreviations are available in Sterman's 1985 and 1999 publications, key acronyms for the stocks are:

- cip - confidence in paradigm,
- a - anomalies,
- pua - puzzles under attack,
- sp - solved puzzles, and
- hsp - historical solved puzzles.

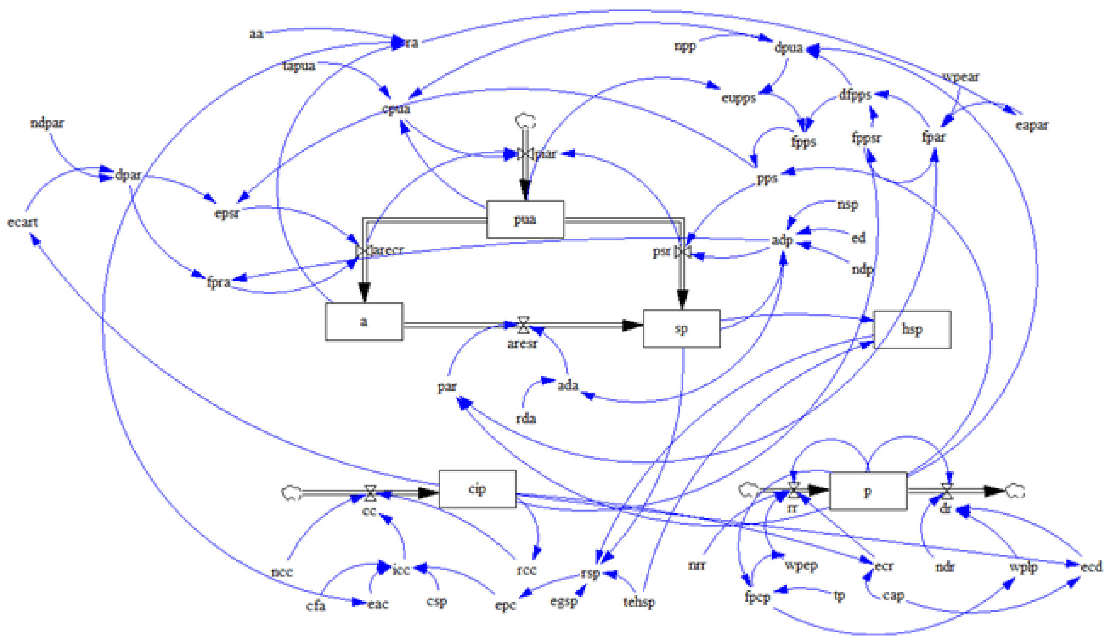


Figure B - 2: Representation in Vensim® of the model listed by Sterman (1985)

The Vensim® model was then coded in NetLogo, (Version 4.0.3) using the following ordered rules:

- compute variables,
- compute flows, and finally
- update stock values via temporary variables so that the order of computation does not affect results (Euler's method).

As illustrated in Table B-3, both of the Vensim® and NetLogo models replicate exactly that originally reported by Sterman in 1985.

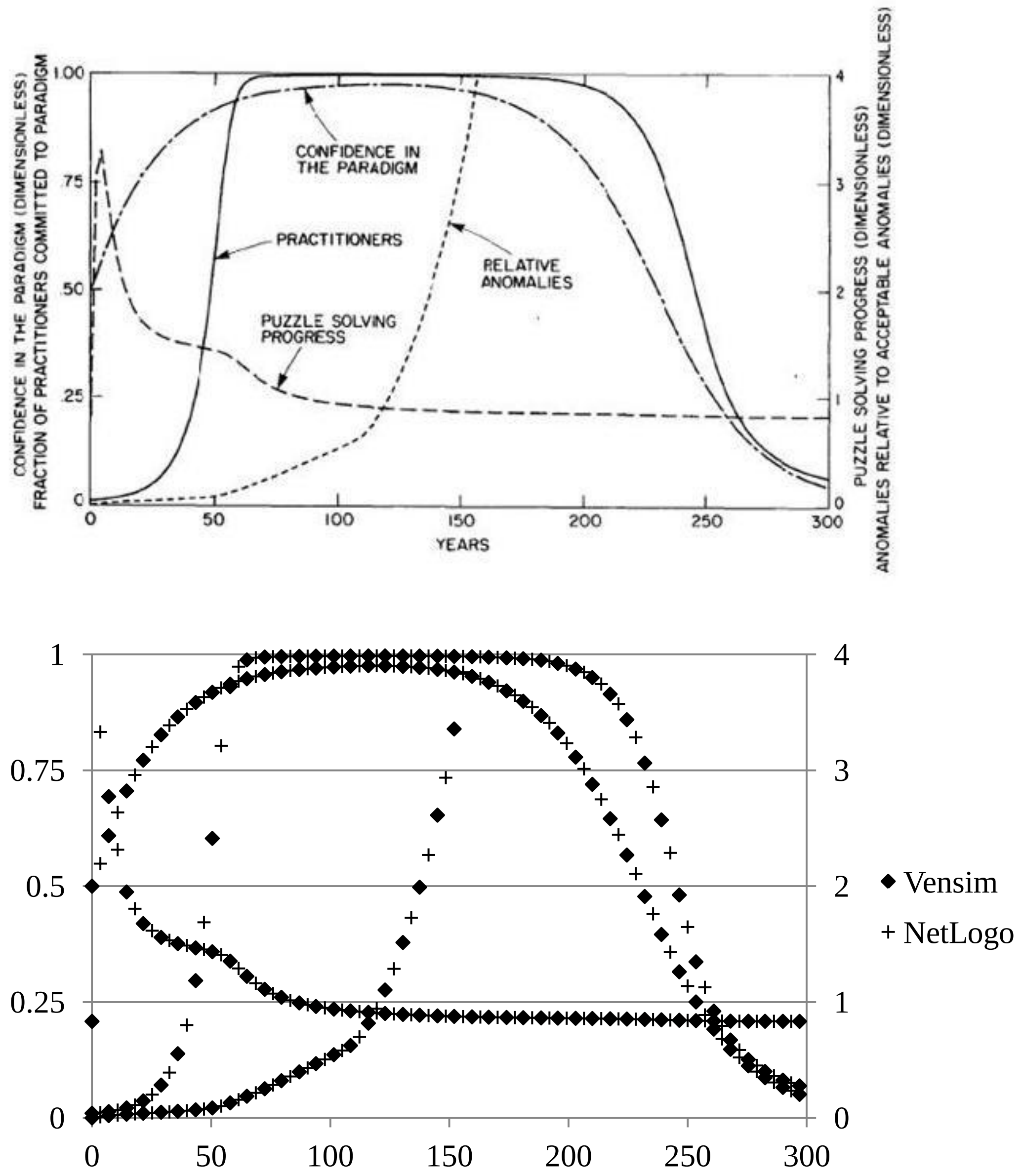
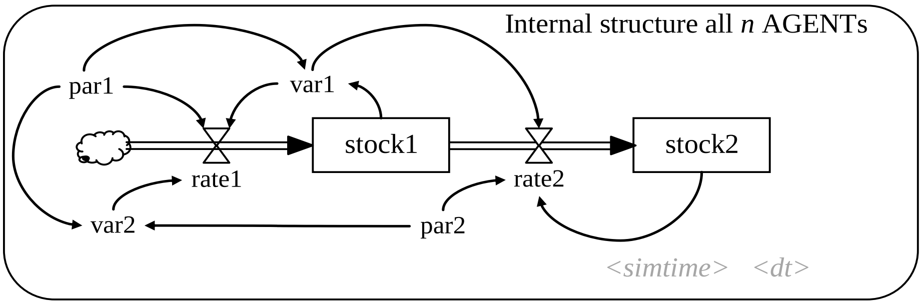


Figure B - 3: Comparison of Vensim® and NetLogo results to that originally reported by Steman (1985) (original results reproduced with permission: Elsevier RightsLink® licence – 3263661433009)

This exercise demonstrated the potential for representing relatively complex SD models within Netlogo. Combined with the reasons discussed previously, this modelling tool was selected for the research reported in this thesis. Drawing from this exercise, a general translation for SD modelling within NetLogo was identified as described in Figure B-4. It should be noted that global variables are represented inside angular ‘< >’ parentheses throughout this thesis.




```
globals [maxTime]
breeds [agents agent]
agents-own [
  stock1 stock2 par1 par2 simTime dt ]
```

At the global level declare global variables and agents with their own variables.

```
to setup
  set maxTime 5
  create-agents n [
    set stock1 0  set stock2 0
    set par1 x     set par2 y
    set dt 0.01    set simTime 0 ]
end
```

Set up function including the creation of *n* agents in which their own internal parameters are, in this exemplar, also initiated.

```
to mainCode
  ….
  while max [simTime] of agents < maxTime] [
    ask agents [sdModel]
    ]
  ….
end
```

Within the main code a call is made to an SD model within the agentset and runs until the global maxTime is reached by one of the agents. In this case they will finish together as *dt* is the same for all.

```
to sdModel
;variables
  let local_var1 var1
  let local_var2 var2
;flows
  let local_rate1 rate1
  let local_rate2 rate2
;stocks
  let new_stock1 stock1 + ( rate1 – rate2) * dt
  let new_stock2 stock2 + (rate2) * dt
  set stock1 new_stock1
  set stock2 new_stock2
;iterate time
  set simTime simTime + dt
end
```

This function is the SD model. The order in which variables, flows and stocks are calculated and set is important and must be followed. The use of let for local variables within functions is also important before agent variables are defined using set.

```
to-report rate1 report f(var1, var2, par1) end
```

calculate rate1

```
to-report rate2 report f(stock2,var1, par2) end
```

calculate rate2

```
to-report var1 report f(stock1, par1) end
```

calculate var1

```
to-report var2 report f(par1, par2) end
```

calculate var2

Figure B - 4: Generic translation of an SD stock and flow diagram into Netlogo

This translation allows rapid representation of SD models within Netlogo, which is useful when investigating different design constructs for hybrid AB-SD models as discussed in later chapters. Whilst, diagrammatic drag-and-drop facilities for SD are available in Netlogo, the author has found direct coding in accordance with this general translation faster and, given the defined structure, straightforward to verify the code and validate models.

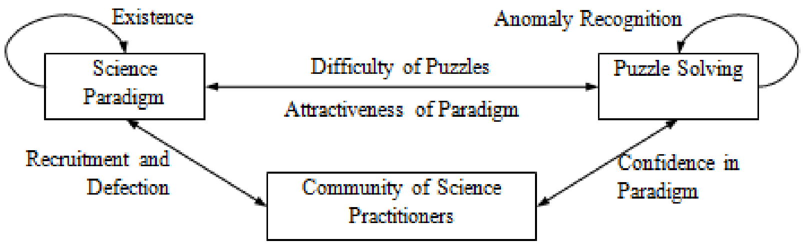
Annex C – Review of 18 Conceptual Models and Model Implementation

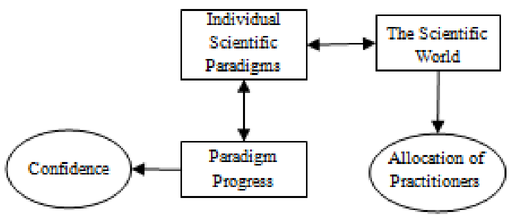
Robinson defines a conceptual model as (Robinson, 2012, p. 13) "… a non-software-specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions and simplifications of the model." Robinson associates objectives with the overarching study in which modelling is exploited and with the model itself. Study objectives capture aspects such as project duration and milestones, resources and customer requirements for example, whereas modelling objectives describe what the modeller is hoping to achieve with the model itself.

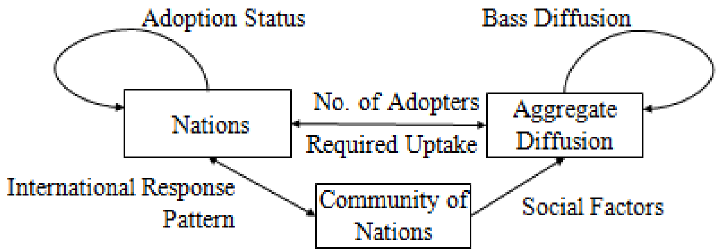
Here, the results of a literature review across a diverse number of application areas is summarised in a series of tabulated forms that capture both Robinson's definition of a conceptual model and an outline review of reported model implementation. An assessment for the potential of using alternative modelling paradigms is also included. For clarity, the form used for this review is summarised in Table C-1.

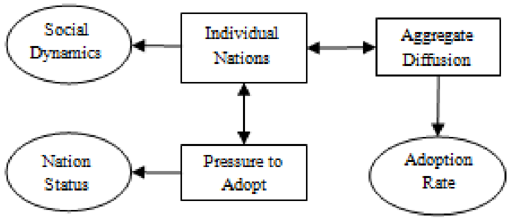
Table C- 1: Form for reviewing the reported content of conceptual models and model implementation plus assessment of alternative options for implementation.

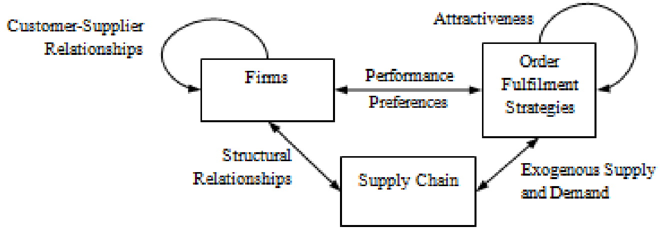
<table>
<tr><td>Author(s) and Reference(s)</td><td colspan="2"></td></tr>
<tr><td>Real World Problem</td><td colspan="2"></td></tr>
<tr><td>Modelling Objectives</td><td colspan="2"></td></tr>
<tr><td>Inputs (Experimental Factors)</td><td colspan="2"></td></tr>
<tr><td>Outputs</td><td colspan="2"></td></tr>
<tr><td>Content</td><td colspan="2">Schematic diagram representing the content of the conceptual model using the proposed general framework (Chapter 4, Figure 4-3).</td></tr>
<tr><td>Assumptions</td><td colspan="2"></td></tr>
<tr><td>Simplifications</td><td colspan="2"></td></tr>
<tr><td>Design Schematic (not all reported outputs shown)</td><td>Implementation</td><td>Alternative Options</td></tr>
<tr><td rowspan="4">Schematic diagram of model as reported.</td><td rowspan="2">Design Class:
Interfaced/Sequential/Integrated</td><td>Sequential/Integrated/Interfaced:</td></tr>
<tr><td>Integrated/Interfaced/Sequential:</td></tr>
<tr><td rowspan="2">Hybrid(AB/SD/DES/CA)/AB/SD
[Modelling Tool(s) used]</td><td>AB: as an option?</td></tr>
<tr><td>SD: as an option?</td></tr>
</table>

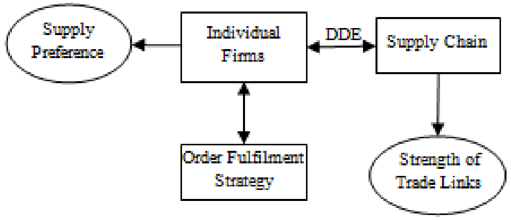
<table>
<tr><td>Author(s) and Reference(s)</td><td>Sterman JD (1985). The growth of knowledge: testing a theory of scientific revolutions with a formal model. Technological Forecasting and Social Change 28, 93-122.
Sterman JD and Wittenberg J (1999). Path dependence, competition and succession in the dynamics of scientific revolution. Organization Science 10, 322-341.</td></tr>
<tr><td>Real World Problem</td><td>Formalising Kuhn's Structure of Scientific Revolutions.</td></tr>
<tr><td>Modelling Objectives</td><td>Determine relative importance of structural versus contextual forces in the birth and death of scientific theories.</td></tr>
<tr><td>Inputs (Experimental Factors)</td><td>Intrinsic versus contingent factors: intrinsic capability; confidence in the dominant scientific paradigm when created; and competition when created (p. 334).</td></tr>
<tr><td>Outputs</td><td>Over time: fraction of practitioners per paradigm; confidence (puzzles solved & relative anomalies) in paradigms; and rise and fall time in practitioner numbers per paradigm over time.</td></tr>
<tr><td>Content</td><td>
</td></tr>
<tr><td>Assumptions</td><td>Crisis in a paradigm reached when sufficient unsolved puzzles are recognized as important anomalies (p. 324).
Average difficulty of puzzles in paradigm increases as number of puzzles solved increases (p. 325).
Population of scientists remains constant (p. 328). A new paradigm has a defined initial state (p. 329).</td></tr>
<tr><td>Simplifications</td><td>Life cycle of a scientific paradigm: emergence; normal science; crisis; and revolution (p. 324).
All paradigms have the same internal structure (p. 325).
Creation of new paradigm is stochastic relative to practitioner activities in the dominant scientific paradigm (p. 329).</td></tr>
</table>

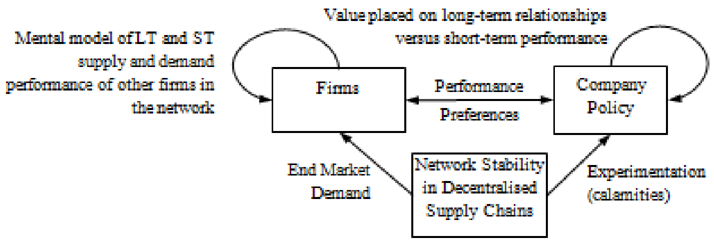
<table>
<tr><td>Design Schematic (not all reported outputs shown)</td><td>Implementation</td><td>Alternative Options</td></tr>
<tr><td rowspan="4">
</td><td rowspan="2">Integrated</td><td>Sequential: No; process has implicit feedback and competition. Positive feedback and path dependence important features here. Objective is to determine relative importance of intrinsic versus contingent factors. The environment and concurrent status of other paradigms key.</td></tr>
<tr><td>Interfaced: No; as above.</td></tr>
<tr><td rowspan="2">SD
[DYNAMO]</td><td>AB: Maybe; Akkermans' argument in regards organisations with complex internal structures could be applied here making a case to reject this approach in this case. On the other hand, Simon suggests "human goal-directed behaviour simply reflects the shape of the environment in which it takes place; only a gross knowledge of characteristics of the human information-processing system is needed to predict it". Scientific paradigms are conceptual with no spatial context, therefore, benefits associated with AB modelling of movement and space would not be utilised.</td></tr>
<tr><td>Hybrid: Yes; maybe a stronger case than for AB implementation.</td></tr>
</table>

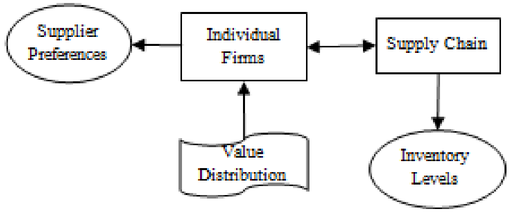
Author(s) and Reference(s)	**Swinerd C and McNaught KR** (in draft). Simulating International Diffusion of Consumer Technology. Technological Forecasting and Social Change.
Real World Problem	International diffusion of technological innovation.
Modelling Objectives	With nations represented as the adopting agent within a social system of nations, determine whether the international adoption of technology innovation can be predicted and what the key system parameters for such predictions are and their values.
Inputs (Experimental Factors)	National measures and associated weightings, extent of geographic influence, importance of social influence over time, relative importance of internal pressure versus social pressure to adopt, and coefficients of innovation and imitation for controlling the aggregate diffusion process.
Outputs	Over time: Aggregate diffusion process; spatial diffusion; individual response; and specific social interactions.
Content	
Assumptions	Reasoned action is a mix of one's own intention and external influence in regards performing specific behaviour. The broad principles of diffusion in the context of individuals and organisations can be applied to nations. All nations wish to wear the Golden Straitjacket.
Simplifications	In regards population mixing, we need not represent the detail of interactions between each citizen from one nation with each citizen from another. The internal characteristics of a nation can be represented in five broad categories. Up to two socioeconomic proxies are sufficient to represent the internal intent of a nation. The internal model representing pressure to adopt is the same for all nations.

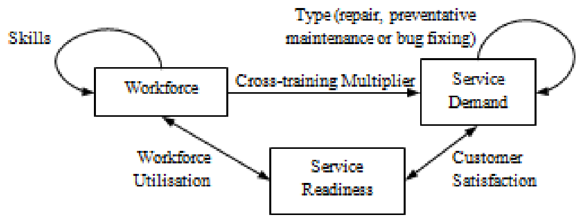
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Integrated	Sequential: no; The international social system of nations is important to individual decision making. The pressure for a nation to adopt depends on the concurrent rate of change in internal and external factors.
		Interfaced: no; as above
	Hybrid AB-SD [NetLogo]	AB: maybe; Akkermans' argument in regards organisations with complex internal structures could be applied here making a case to reject this approach in this case. On the other hand, Simon suggests "human goal-directed behaviour simply reflects the shape of the environment in which it takes place; only a gross knowledge of characteristics of the human information-processing system is needed to predict it". Whilst social influence, including influence from near neighbours, is shown to be an important factor in international diffusion, nations are fixed in place and, therefore, benefits associated with AB modelling of movement would not be utilised.
		SD: yes; as demonstrated by Sterman and Wittenberg but would need a look-up-table, or similar approach, for all bi-lateral measures from which to weight social influence between nation pairs.

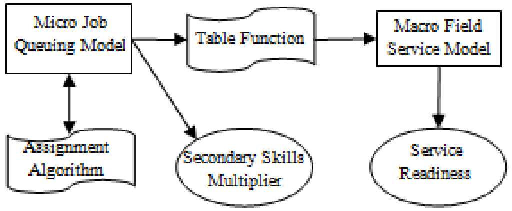
Author(s) and Reference(s)	**Schieritz N and Größler A** (2003). Emergent structures in supply chains - a study integrating agent-based and system dynamics modelling. System Sciences, 2003. Proceedings of the 36th Annual Hawaii International Conference on System Sciences.
Real World Problem	Support decision-making in supply chains (abstract).
Modelling Objectives	Systematic testing of supply chain strategies (using a hybrid modelling approach to improve modelling performance (p. 1)).
Inputs (Experimental Factors)	Attractiveness of supplier (delivery time, volumes) (p. 3).
Outputs	Variation of order fulfilment strategy; variation of attractiveness decay time.
Content	
Assumptions	Ordering module (based on work of Sterman) is sufficient (p. 4).
Simplifications	As modelling 'downstream' supply chain, manufacturing sector not considered (p. 4). Two shipment strategies assessed: First-in-first-out; and relationship (based on past trade volumes) (p. 3). All output from a supplier provide input to a customer (p. 4). Basic internal structure of agents is the same – parameterisation and allocation of order fulfilment strategies used to differentiate firms (agents).

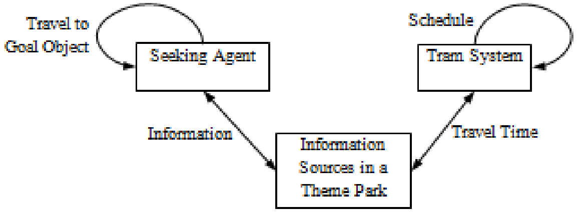
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Integrated	Sequential: No; Concurrent processes of firm behaviour and supply chain dynamics needed.
		Interfaced: No; As above.
	Hybrid Discrete AB-SD [em-Plant™-Vensim®]	SD: Maybe; Forrester's work on four-layer supply chains quoted (p. 2). Observed disadvantage is that the structure of the supply chain has to be known from the outset (p. 7). A company in a supply chain can switch from one supplier to another or suppliers can enter or exit the market.
		AB: Yes; "dynamics of the system arises from the interactions of agents whereby the behaviour of an agent is determined by its cognitive structure, its schema." (p. 2)

Author(s) and Reference(s)	**Akkermans H** (2001). Emergent supply networks: system dynamics simulation of adaptive supply agents, Proceedings of the 34th Annual Hawaii International Conference on System Sciences.
Real World Problem	Supporting decision making in decentralised manufacturing supply networks (p. 1).
Modelling Objectives	Generate tentative management rules for companies operating in decentralised supply chains (p. 9).
Inputs (Experimental Factors)	Value placed on long-term relationships versus short-term performance.
Outputs	Network stability (p. 5); Changes in relative supplier/customer preference (p. 5); Cumulative shipments; and Aggregate network metrics (i.e. inventory levels at different tiers of the supply network) (p. 4).
Content	
Assumptions	Internal behaviour of firms is the same and consistent: 1) how much product to ship?; 2) how much production is needed?; and 3) how much material is needed? (p. 3)
Simplifications	Expected future market demand equals exponentially smoothed values for recent orders (p. 3). Firms have no real capacity constraints (p. 8). No increases in product functionality or fluctuations in production and product quality represented (p. 8). All firms manufacture the same product throughout and continue to do this well (p. 8). No switching costs associated with changing suppliers (p. 8). Firms do not perish nor are mergers and acquisitions represented (p. 8). Agents (firms) do not breed nor is there rule discovery (p. 8).

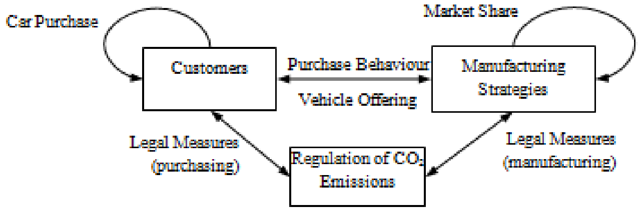
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Integrated	Sequential: No; Concurrent processes of firm behaviour and supply chain dynamics needed.
		Interfaced: No; As above.
	SD [Vensim®]	AB: Maybe; Rejected by modeller due to complex ordering and production behaviour of firms (agents) plus well-tested and documented generic models of such behaviours available in SD textbook theory (p. 3). The supply network here remains constant with no firms perishing or new firms becoming established which might be well handled in AB approach although the Sterman and Wittenberg example suggests that this could be achieved in SD also.
		Hybrid: Yes; The complexity of agent schema could be captured by SD within an AB network as per Swinerd and McNaught example.

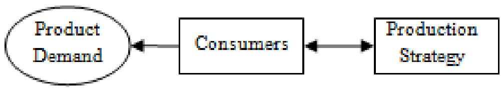
Author(s) and Reference(s)	**Homer JB** (1999). Macro- and micro-modelling of field service dynamics. System Dynamics Review 15, 139-162.
Real World Problem	Workforce planning for field service provision (p. 139).
Modelling Objectives	Develop cost-effective strategies for service readiness whilst maintaining customer satisfaction (p. 140).
Inputs (Experimental Factors)	Workforce size; Cross-training of service engineers; Product quality reducing need for service provisions (p. 140).
Outputs	Macro: Workforce utilisation (p. 144); Service readiness versus cross-training strategy (p. 157) and Micro: Job queue dynamics (p. 151).
Content	
Assumptions	Macro modelling: Agreed representation of service provision is sufficient (implicit assumption); skill-building processes are structurally identical and parametrically similar for all engineers and product types (note 1 p. 160). Micro modelling: Job queuing model for the stable regional hub used as a baseline represents most hubs across the country (p. 152); mean time between service for each product type is constant (p. 149); cross-trained engineers assigned jobs for products trained on in roughly equal proportion (note 3 p. 161).
Simplifications	Macro modelling: Senior engineers selected for cross-training whereas in reality some juniors may be trained with insufficient seniors in the workforce (note 2 p. 161). Micro modelling: Nature of service job types comprise a single repair job or a single PM job and any number of bug fixes (p. 150).

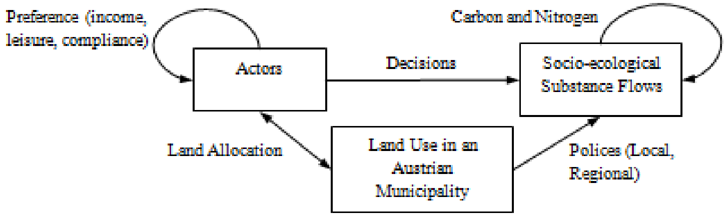
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Sequential (macro) {Integrated (micro)}	Interfaced: No; table function provides input to the SD model.
		Integrated: No; aim here is to support strategic decision making. Maintaining an understandable model at one level of aggregation is, therefore, a key objective. Table function needed as an input before strategic model could be run. Should case for dynamic queuing model be made then opportunity for increased integration.
	SD [Vensim®]	AB: No; task was to agree stable structure for field service provision then test for different management strategies within this context. Dynamic response to different strategies was of interest not emergence within the field service structure itself.
		Hybrid: No; as above.

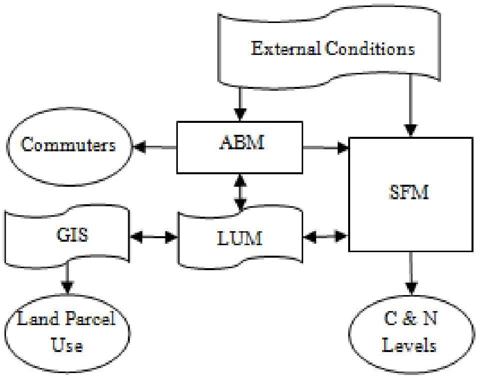
Author(s) and Reference(s)	**Dubiel B and Tsimhoni O** (2005). Integrating agent based modeling into a discrete event simulation. Proceedings of the 2005 Winter Simulation Conference, pp 1029 – 1037.
Real World Problem	Modelling free moving agents to supplement extant DES models of service and transportation, especially in the context of theme parks.
Modelling Objectives	To represent human-like movement and travel (p. 1029) and integrate this with a DES model of a transportation system.
Inputs (Experimental Factors)	Start position; Start direction.
Outputs	Sighting information sources to achieve greatest coverage with fewest resources (p. 1034); Agent decision state versus time (p. 1035).
Content	
Assumptions	Agent search functions: Motion is the most prominent factor in search algorithm (p. 1034).
Simplifications	Representation of human perception, decision making and movement. Both agent types have the same overall design (p. 1030). Agent visual perception: Defined prominence of objects represented with a single salience value (p. 1033); Maximum distance at which agents can differentiate between objects set to 400ft throughout (p. 1033). Agent decision logic: decision states defined (p. 1033); sociability parameter to account for agent's tendency to approach people for advice rather than a map (p. 1033). Agent movement: hearing distance threshold set to 10ft (p. 1034) Weak interactions: agent must be within 2ft of a map in order to gain information which is interpreted correctly in 70% of such interactions (p. 1034). Strong interactions: Information interpreted correctly in 90% of such interactions (p. 1035).

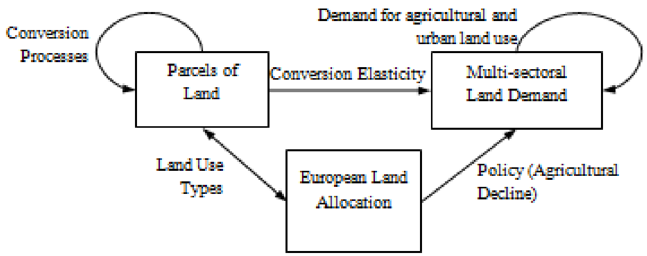
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Interfaced	Sequential: No; Agent could walk to goal object or use tram depending on information gleaned within the environment. There is no set process where sequential modelling could be used here.
		Integrated: Yes; if the tram system exhibited dynamic changes such as faults then feedback between the tram system and information agents in the theme park (the environment) could add value. Otherwise, the interface design is probably the preferred choice with the travelling agent either walking or on the tram.
	Hybrid AB-DES [AutoMod]	AB: Yes; Author's conclude that hybrid approach needed where the separate modelling paradigms could not have achieved the same results (p. 1036) – but no further discussion of this aspect. A tram agent could, however, be implemented within an ABM that followed a set path and used set timings to carry a set number of travellers.
		SD (DES): No; Aim is to capture freedom of movement and associated decision making at appropriate non-prescribed times; modelling of intelligent entities within an environment (p. 1029).

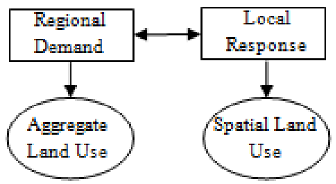
Author(s) and Reference(s)	**Kieckhäfer K, Walther G, Axmann J and Spengler T** (2009). Integrating agent-based simulation and system dynamics to support product strategy decisions in the automotive industry. Proceedings of the 2009 Winter Simulation Conference, pp 1433-1443. Kieckhäfer K, Wachter K, Axmann J and Spengler TS (2012). Model-based decision support for future OEM power-train portfolios: academic solutions for practical requirements. Proceedings of the 2012 Winter Simulation Conference, pp 1433-1443. http://www.systemdynamics.org/conferences/2012/proceed/papers/P1127.pdf
Real World Problem	Develop a framework for the analysis of product strategies in the automotive industry with special regard to alternative fuel and powertrain technologies.
Modelling Objectives	Decision-support capturing interactions between vehicle supply and demand, competitor behaviour, supply of infrastructure, macro-economic and regulatory conditions.
Inputs (Experimental Factors)	Crude oil price; cost of production (p. 1439). Introduction of technology options plus reduction in conventional options [p. 12].
Outputs	Change in purchasing behaviour as a function of customer and manufacturing polices (p. 1441)
Content	
Assumptions	Manufacturer's offerings comprise two powertrains and two vehicle class options (p. 1439) [p. 6] plus time to introduction [p. 6]. Calculation of purchase price and cruising range of a battery electric vehicle defined [p. 9]. OEMs do not adjust their product offerings continuously [p. 11].
Simplifications	Vehicles are described by price and range (p. 1439) [p. 8]. Population characterised by rich and poor groupings (p. 1439) by age, environmental awareness and road use [p. 8]. Holding time for a vehicle is determined by an exponentially distributed random variable [p. 8].

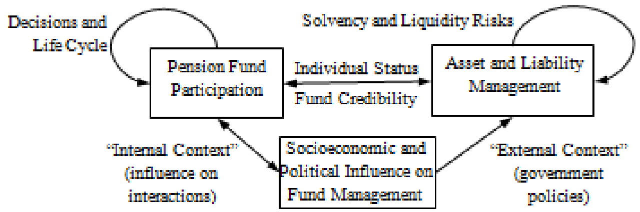
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Integrated	Sequential:
		Integrated:
	Hybrid AB-SD [Anylogic®]	AB: no; In their 2012 paper, the authors observe that AB models focus on heterogeneous consumer behaviour but this is not integrated with business and technology developments. They argue, therefore, that a hybrid approach is required.
		SD (DES): No; Author's state: "Modeling a complete product portfolio is at least very difficult with System Dynamics." [sic] Also they observe that consumer behaviour should not be modelling homogeneously (p. 1437). Here they "the model allows both, a distinction between several consumer groups as well as the consideration of a detailed vehicle fleet." (p. 1437). However, if market potential is huge then there may be a case for aggregation of consumer behaviour?

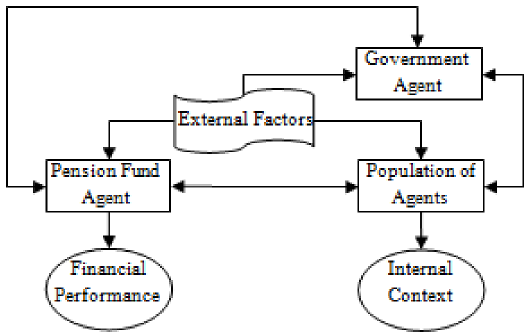
Author(s) and Reference(s)	**Gaube V** et al (2009). Combining agent-based and stock-flow modelling approaches in a participative analysis of the integrated land system in Reichraming, Austria. Landscape Ecol 24, 1149–1165.
Real World Problem	Ecological Compatibility of Regional Development in the municipality of Reichraming, Upper Austria (p. 1150).
Modelling Objectives	Understanding feedbacks between socioeconomic and natural components of the integrated land system in regards sustainability science (p. 1150).
Inputs (Experimental Factors)	Economic factors: agricultural or energy prices, political factors: subsidies and regulations, and social factors: leisure time preferences and minimum income requirements. (p. 1151).
Outputs	"indicators of land-use change, greenhouse gas (GHG) emissions and the aggregated C or N balance as well as indicators of socioeconomic parameters such as municipality budget and household numbers" (p. 1152).
Content	
Assumptions	Co-operation between farms and the national park have a positive impact on the attractiveness of Reichraming to tourists (p. 1153). "Whenever the requirements of a consumer and a supplier match to at least 70%, with respect to the size of the area, a transaction can proceed" (p. 1154)
Simplifications	All process beyond the municipal level are outside the model represented as input values (p. 1152). Impact of climate change not included (p. 1152). Aggregated agents used to represent a group of single actors such as households and tourists for example (p. 1153).

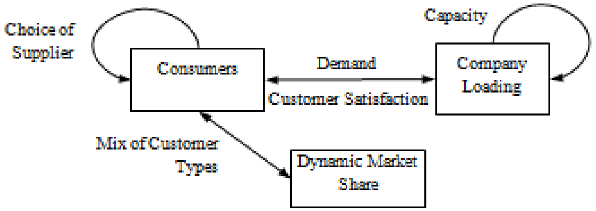
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Integrated	Sequential: no; Given the explicit modelling objective (see above), this model provides dynamic adjustment of external conditions and, via the Land Use Module (LUM), real-time information exchange between the Agent-based Module (ABM) and Stock and Flow Module (SFM).
		Interfaced: no; as above.
	Hybrid AB-SD [AnyLogic®]	AB: no; It would not be a realistic proposition to represent the aggregate stock and flow of Carbon and Nitrogen within ABM.
		SD: possibly; Households and tourists are aggregated into one agent and, therefore, could be represented in an SD module. Farms are, however, represented as individual agents. Even though they are essentially static, they represent a spatial context for decisions in regards land use. The spatial representation of land use is provided by a GIS that interfaced with a database in which land parcels are represented by ID number.

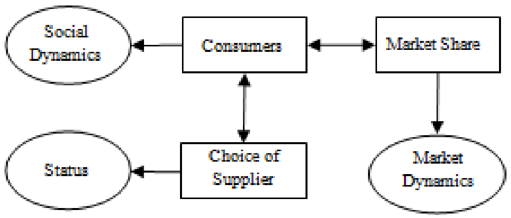
Author(s) and Reference(s)	**Verburg PH and Overmars KP** (2009). Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape Ecol 24, 1167–1181.
Real World Problem	Predicting land use in Europe under a range of prevailing conditions.
Modelling Objectives	"Simulation models at regional to global scales are often incapable of including locally determined processes of land use change" (p. 1167). Here the objective is to "integrate top-down allocation of land use change with bottom-up algorithms of vegetation dynamics determined by local conditions" (p. 1168).
Inputs (Experimental Factors)	Location and specific local conditions (conversion elasticity, etc.), land conversion matrix (agriculture – abandoned – scrub – forest) (p. 1170).
Outputs	Mapped land use allocations as a function of time (p. 1174). Aggregate land use as a function of time (p. 1177).
Content	
Assumptions	Nothing noted.
Simplifications	Land use allocated one of three types: agricultural and urban demand and no-demand (p. 1169).

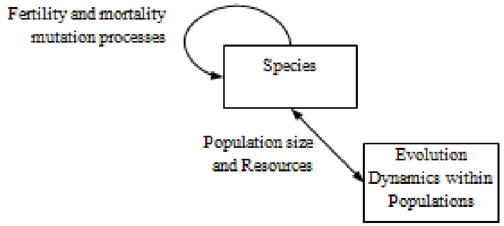
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Integrated	Sequential: maybe; However, the authors argue: "The dynamics of agricultural area are, in large parts of the world, a result of changes in (global) demand and market conditions of food, feed and energy. For other land use types, especially (semi-) natural land use types, it is more difficult to determine the changes in a top-down approach." (p. 1168) As with the
		Interfaced: no; local response must be in context of established regional demand.
	Hybrid Aggregate-Spatial [Bespoke Dyna-CLUE]	AB: same argument as per He, et al.
		SD: same argument as per He, et al.

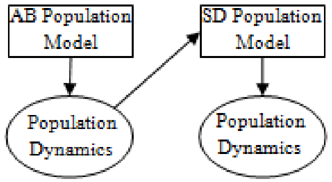
Author(s) and Reference(s)	**Chaim RM and Streit RE** (2008). Pension funds governance: combining SD, agent based modelling and fuzzy logic to address dynamic asset and liability management (ALM) problem. Proceedings of the 26th International Conference of the System Dynamics Society.
Real World Problem	Asset and Liability Management (ALM) approach for pension funds (p. 2).
Modelling Objectives	Combine modelling methods and techniques to study pension fund population models and the influence of subjective factors over it (p. 1).
Inputs (Experimental Factors)	Mortality, fund withdrawal, new participation, retirement, and disability ratios.
Outputs	Pension fund solvency, credibility and wealth (p. 7).
Content	
Assumptions	Pension fund credibility rating influences new participation (p. 10).
Simplifications	A pensioner is exposed just to mortality risks opposed to other agents who are exposed to mortality, disability, withdrawal and retirement risks. (p. 10). Agent deliberation (what to do) and planning (how to do it) processes combined (p. 12).

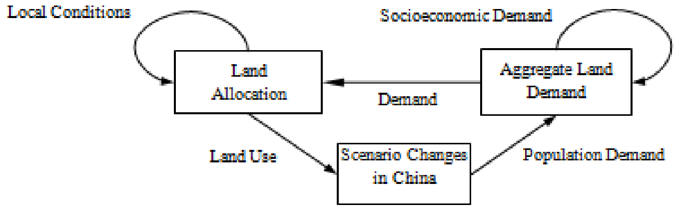
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Integrated	Sequential: no; concurrent population and pension fund dynamics at play.
		Interfaced: no; as above.
	Hybrid AB-SD	AB: Possibly; Providing agents with complex internal schema can be represented. This has been shown in the Swinerd and Mcnaught example.
		SD: Possibly; the Duggan example possibly applies.

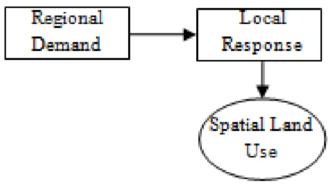
Author(s) and Reference(s)	**Duggan J** (2008a). Equation-based policy optimization for agent-oriented system dynamics models. System Dynamics Review 24, 97-118.
Real World Problem	Validation of the Continuous Agent-based Modelling Architecture (p. 7).
Modelling Objectives	Construct a market dynamics model with a heterogeneous agent population (p. 7 and p. 12).
Inputs (Experimental Factors)	Agent decision making and market share advantage (p. 8 and p. 12).
Outputs	Market share as a function of agent type and societal spatial distribution (p. 13).
Content	
Assumptions	The case study is sufficient to validate the CABM architecture and is representative of challenging ABM designs. For example, the division of the population into age based cohorts with assigned confidence thresholds and adjustment times is sufficient to demonstrate a heterogeneous agent population (p. 12).
Simplifications	Two competing companies only (p. 7). Market potential is constant (p. 7). Three different types of agents (consumers) that share common features (p. 8).

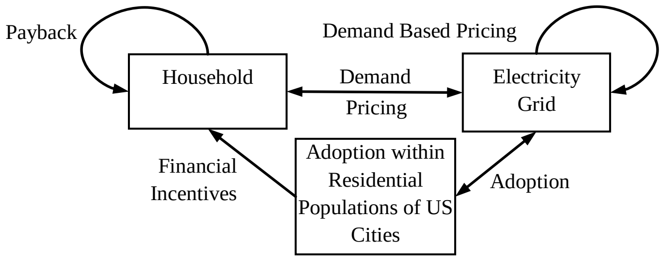
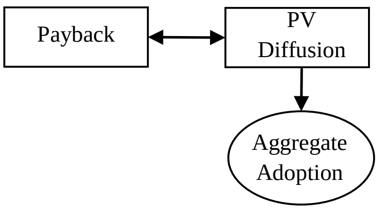
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Integrated	Sequential: no; Consumers are operating with a social structure with decision making influence by neighbours. This influence is dynamic and depending upon the heterogeneity of the society being modelling, emergent behaviour is not predicable.
		Interfaced: no; as above.
	Hybrid SD [CABM]	AB: Yes; capturing the aggregate market share of competing companies is feasible within AB modelling. However, this model is used to validate the CABM Architecture. It might be that complex internal decision making as available through CABM might become challenging within ABM.
		SD: no; The author states that "SD tools are not amenable to the construction of large scale agent societies" (p. 2) and proposes a solution through CABM, which is based on the SD paradigm.

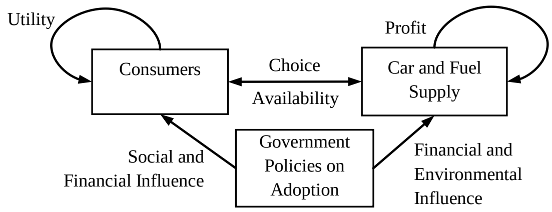
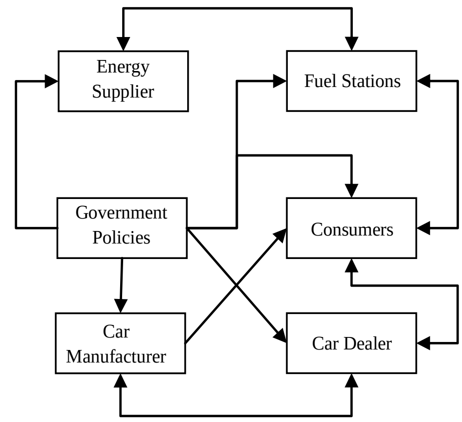
Author(s) and Reference(s)	**Schieritz N and Milling PM** (2009). Agents first! Using agent-based simulation to identify and quantify macro structures. In Qudrat-Ullah, H, Spector MJ and Davidsen PI (eds), Complex Decision Making - Theory and Practice. Springer: London, pp 139-152.
Real World Problem	To explore the potential for agent based modelling to identify macro level causal structure (p. 144).
Modelling Objectives	Develop a macro theory for the evolution of a population (p. 144).
Inputs (Experimental Factors)	Mutation rate, deterioration rate, initial population sizes (p. 145).
Outputs	Aggregate specie populations as a function of time (p. 146).
Content	
Assumptions	None noted; although this work explores the integration of modelling paradigms rather than a specific real world problem per se.
Simplifications	Two species competing for available resources (p. 144).

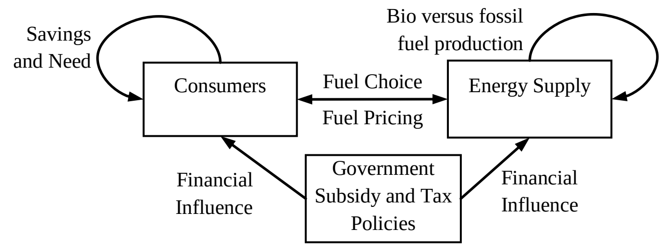
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Sequential	Interfaced: no; the aim here was to determine whether an SD model could be designed based on observations of emergent behaviour from an AB model.
		Integrated: not applicable; this is an academic study to see whether an SD model can be built on the basis of lessons learnt from an AB model.
	Hybrid AB-SD [not sated]	AB: Yes; AB and SD models demonstrated that they can show the same system dynamic behaviours in this case.
		SD: Yes; as above.

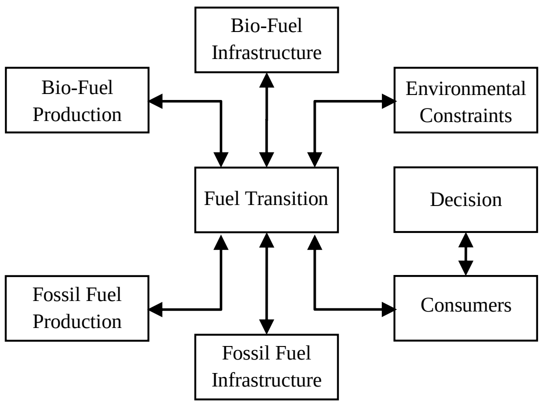
Author(s) and Reference(s)	**He C, Pan Y, Shi P, Li X, Chen J, Li Y and Li** J (2004). Developing land use scenario dynamics model by the integration of system dynamics model and cellular automata model. Proceedings of the Geoscience and Remote Sensing Symposium 2004, pp 2647-2650.
Real World Problem	Impact of scenario changes on land use in China over a 50 year period (p. 2647).
Modelling Objectives	Capturing system complexities that arise from the "interaction in space and time of biophysical factors and human factors at different scales" by combining top-down system dynamics and bottom-up cellular automata modelling approaches. (p. 2647).
Inputs (Experimental Factors)	GDP, Change in Population, Food self-supplying ratio and grain productivity (p. 2649).
Outputs	Land use maps as a function of time (p. 2650).
Content	
Assumptions	Land use change is predominantly driven by population, GDP, market adjustment, technology advance and land use policy (p. 2649).
Simplifications	Land use types are: urban, cultivated land, grassland, forest land and unused land (p. 2649). Food self-supply is used to represent market adjustment and grain productivity is used to represent technology advance (p. 2649).

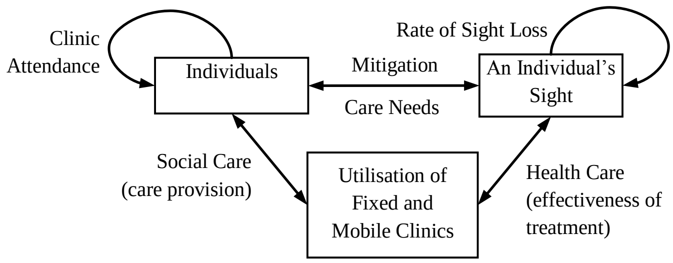
Design Schematic (not all reported outputs shown)	**Implementation**	**Alternative Options**
	Sequential (pp. 2647-2648)	Interfaced: no; the local (spatial) response must be based on an established regional demand.
		Integrated: yes; as per Verburg and Overmars example but the advantages of doing so are not apparent.
	Hybrid SD-CA [LUSD]	AB: maybe not; As the authors argue (p. 2647) in regards CA, these bottom-up modelling paradigms are not well placed to capture macro-scale driving forces.
		SD: maybe not; As the authors argue (p. 2647) in regards SD, top-down modelling paradigms are not well placed to capture spatial process due to the wealth of data needed (in the context of land use). I am not clear here as the agent-orientated SD approach might work (Sterman and Wittenberg, Swinerd and McNaught and Duggan)?

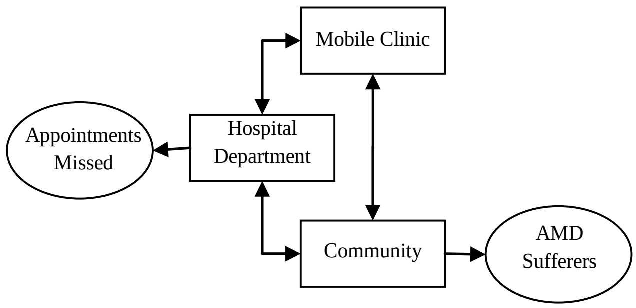
Author(s) and Reference(s)	**Zhao J, Mazhari E, Celik N and Son Y-J** (2011). Hybrid agent-based simulation for policy evaluation of solar power generation systems. Simulation Modelling Practice and Theory 19 p2189–2205.
Real World Problem	Impact of policy options on the residential adoption of PV solar panels.
Modelling Objectives	Detailed analysis of adoption rates of solar power electricity generation (PV adoption)
Inputs (Experimental Factors)	Household adoption threshold, PV price, Incentives,
Outputs	Aggregate adoption, Aggregate PV electricity generation
Content	
Implementation	**Alternative Options**
Integrated within Sequential (but note that an integrated AB-SD hourly payback calculation model feeds an AB household adoption model (i.e. an integrated model within a sequential model)	Interfaced: no; payback calculations needed before adoption process modelled.
	Sequential: not applicable as this is a hybrid-hybrid model
	SD: no; Authors state: "ABM has been more favourable and powerful in modelling the social systems" (p. 2199); "ABM reduces the restrictions and unrealistic assumptions (e.g. linearity, homogeneity, normality, stationary, etc.)" (p. 2199); "the centrality of agents in ABM, facilitates expressing data and knowledge about behaviour, motivation and relationships associated with agents. This makes ABM a natural tool for social science" (p. 2200); and "very powerful tool in modelling emergent conditions especially in complex systems." (p. 2200).
	AB: no; authors wish to include the influence of electricity grid dynamics ("hourly energy transition among PV system generation, household demand and local electricity grid."(p. 2193)) and pricing incentives on payback calculations.

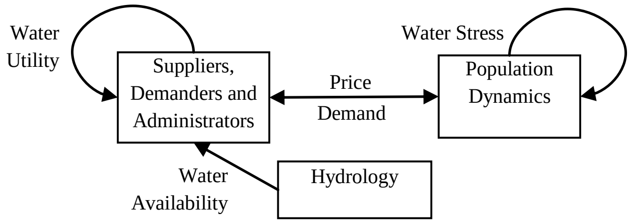
Author(s) and Reference(s)	**Shafiei E, Stefansson H, Ásgeirsson EI, Davidsdottir B and Raberto M** (2012). A hybrid modeling framework for diffusion of alternative fuel vehicles. Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International p1071-1076.
Real World Problem	Evaluating the transitions toward sustainable alternative fuel vehicles (p. 1071).
Modelling Objectives	Comprehensive analysis of energy and transportation system through a hybrid AB-SD model.
Inputs (Experimental Factors)	Supply side production costs demand and profit. Government influence.
Outputs	Inform "policymaking at different levels and spatial scales" (p. 1076).
Content	
Implementation	**Alternative Options**
Integrated	Interfaced: no; concurrent fuel (and energy supply) and car (and manufacturing) sales with consumer response.
	Sequential: as above.
	SD: no; Authors state: SD not suitable for consumers as SD does not capture heterogeneity, self-organisation or the influence of social networks. (p. 1073 and p. 1075).
	AB: no; the authors make a case for using SD to represent energy suppliers, car manufacturers and also car dealers; in regards dealers stating "… mostly rely on the pattern of macro level variables such as consumers' total demand, available vehicles and prices…" making SD more appropriate (p. 1072).

Author(s) and Reference(s)	**Meza CMC and Dijkema GPJ** (2008).Modelling infrastructure systems: A hybrid approach for system transition. Infrastructure Systems and Services: Building Networks for a Brighter Future (INFRA).
Real World Problem	Understanding the impact of transitions in energy infrastructures. (p. 5)
Modelling Objectives	"… to model aggregate dynamics of a system and a system's environment where possible, while at the same time preserving the best representation of the heterogeneity that is created by the social network of actors and their decisions." (p. 5)
Inputs (Experimental Factors)	Agent income, expenses, subsidies, taxes, fuel need and price (pp. 5-6). Delay in information flow representing bounded rationality of agents (p. 6).
Outputs	"…This flexible approach allows focusing not only on the macro-, meso- or micro-level, but also on the interactions between levels in the form of information feedbacks." (p. 6).
Content	

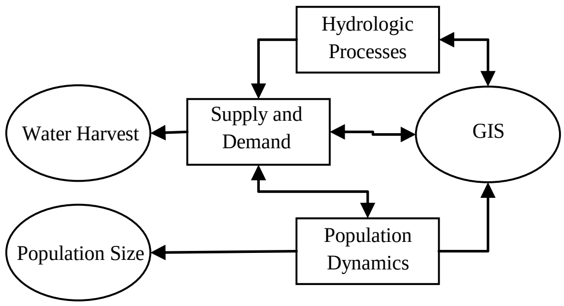
Implementation	**Alternative Options**
Integrated	Interfaced: no; concurrency (with time delays)
	Sequential: as above.
	SD: no; "AB models are suitable for modelling discrete events and, when included in continuous systems models, they reflect better the spontaneous character of decisions."(p. 5)
	AB: no; limited scope to capture the aggregate dynamics of energy supply.

<table>
<tr><td>Author(s) and Reference(s)</td><td>Viana J, Rossiter S, Channon AA, Brailsford SC and Lotery A (2012). A MULTI-PARADIGM, WHOLE SYSTEM VIEW OF HEALTH AND SOCIAL CARE FOR AGE-RELATED MACULAR DEGENERATION. Proceedings of the 2012 Winter Simulation Conference C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A.M. Uhrmacher, eds.</td></tr>
<tr><td>Real World Problem</td><td>Healthcare management of age-related macular degeneration. (p. 1)</td></tr>
<tr><td>Modelling Objectives</td><td>“The model permits a ‘whole system’ societal view” (p. 1).</td></tr>
<tr><td>Inputs (Experimental Factors)</td><td>Social care need and provision, Ophthalmology department efficiency, and Sight loss and AMD Stages (p. 4).</td></tr>
<tr><td>Outputs</td><td>“Length of stay in the clinic, AMD-suffering population size and mortality,
Numbers of missed injections, AMD stage distribution in the population,
Numbers of patients treated and quality criteria for timeliness of appointments, Care provision types distribution in the population, Utilization of Ophthalmology resources, Sight level distribution in the population and
Care need level distribution in the population.” (p. 7)</td></tr>
<tr><td>Content (please represent your model replacing the text as appropriate)</td><td>
</td></tr>
</table>

<table>
<tr><th>Implementation</th><th>Alternative Options</th></tr>
<tr><td rowspan="2">Design Class: Integrated</td><td>Sequential: no; concurrent interaction between modules.</td></tr>
<tr><td>Interfaced: no; dependency between modules and also cross influence of particular interest.</td></tr>
<tr><td rowspan="2">
</td><td>AB: probably not; Authors’ state: “The modelling here is primarily motivated by using the best combination of tools, rather than any claim of novel hybridization. By ‘best’, we mean using the modelling paradigm which most cleanly implements the conceptual design we had in mind for each sub-system.” (p. 3).</td></tr>
<tr><td>SD: probably not; as above – but not sure answers ever clear to why not another paradigm – it is likely that you could implement any model in any other paradigm even though sometimes this might be inefficient.</td></tr>
</table>

<table>
<tr><td>Author(s) and Reference(s)</td><td>Nikolic VV, Simonovic SP and Milicevic DB (2013). Analytical Support for Integrated Water Resources Management: A New Method for Addressing Spatial and Temporal Variability. Water Resour Manage 27: 401–417 doi:10.1007/s11269-012-0193-z</td></tr>
<tr><td>Real World Problem</td><td>Integrated Water Resources Management (p. 401).</td></tr>
<tr><td>Modelling Objectives</td><td>Systematic approach (p. 403) with “integrated consideration of spatial and temporal variability” (p. 404).</td></tr>
<tr><td>Inputs (Experimental Factors)</td><td>Rainfall, population growth, agricultural production strategies (p. 413).</td></tr>
<tr><td>Outputs</td><td>Harvest (tonnage per hectare), water-stress metrics, population dynamics (p. 413).</td></tr>
<tr><td>Content</td><td>


</td></tr>
</table>

<table>
<tr><th>Implementation</th><th>Alternative Options</th></tr>
<tr><td rowspan="2">Design Class: Integrated</td><td>Sequential: no; concurrency.</td></tr>
<tr><td>Interfaced: no; as above.</td></tr>
<tr><td rowspan="2">Modelling Paradigm: hybrid SD-AB)
[NetLogo]


</td><td>AB:</td></tr>
<tr><td>SD: no; authors state “… inability to capture spatial dynamics …” (p. 404)</td></tr>
</table>

Annex D – Dynamic Hybrid Modelling

This annex provides some initial ideas for the design and implementation of computer models that change their architectural configuration during the course of a simulation. As will be discussed, this concept is likely to be most beneficial when looking to reduce computational demand.

As introduced by Swinerd and McNaught (2012a, p. 131), there may be potential in event reconfigurable hybrid design concepts. Described here as 'dynamic hybrid models', one concept is to incorporate time or event driven reconfiguration of a hybrid model. This concept reflects the potential for optimal modelling where the 'nature' of the system changes over time or at specified events. For example, in considering the diffusion of innovations, Rogers (2003) describes how population demographics and social interactions are significant until a critical aggregate condition for product adoption has been achieved. Thereafter, a wholly aggregated model is sufficient to represent what becomes a (Rogers, 2003, pp. 343-357) "self-sustaining" diffusion process. Similarly, Rahmandad (2004) observes that specific social network structure strongly conditions the probability of an epidemic taking off in comparing SD and AB models. Figure D-1 illustrates an event trigger switching in or out the 'parameters with emergent behaviour' design concept of the integrated hybrid design.

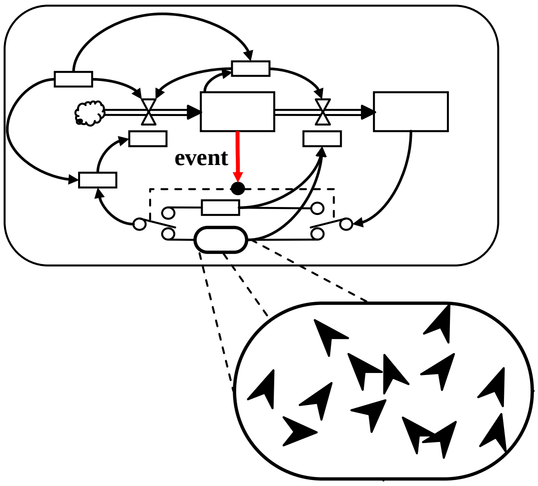


Figure D- 1: Dynamic hybrid modelling: 'event reconfiguration'

This switching concept is further described in the work of Bobashev et al. (2007) who explore the potential for using thresholds to switch between ABS and SD models. The model they describe represents cities linked through air travel in the context of modelling epidemics. The concept proposed originates from the premise that when there are many active agents, the law of large numbers and central limit theorem could be applicable. They observe that such a modelling approach would be more computationally efficient, especially where the number of agents being modelled is very large. The paper also introduces the concept of dynamic threshold switching for each city, whereby the ABS or SD representation is switched in or out depending upon the number of local agents (in that city) that are 'active', i.e. exposed or infectious. Levin and Levin (2003) explore the potential for a finite-state-machine (FSM) to switch between modes, which are represented by SD modules, of a continuous system. They provide an illustrated example of an FSM controlling modes within an SD model which represents the controlled volume and water temperature of a bath. This model is wholly constructed within the SD modelling environment. There are four discrete modes within the SD model controlled by the FSM, representing heating control (ON or OFF) and drain control (OPEN or CLOSED).

On considering Levin and Levin's model and Schieritz and Gröβler's (2003) AB-SD model of a supply chain, it might be that the dynamic hybrid model concept could be used to compensate for the fixed structure of SD models. Whilst the fixed structure of SD models is often cited as a potential benefit, is also used for a reason not to employ SD. In the same way that Schietriz and Gröβler's model allows a supply network to dynamically change via the links between tiered companies, the structure of SD models could change also as illustrated in Figure D-2. The concept here is that stocks are linked by 'agent flows' that will link stocks on the basis of system status. In the simple illustrated example, stock1 will be linked with any of the other stocks based on defined joining rules for the model.

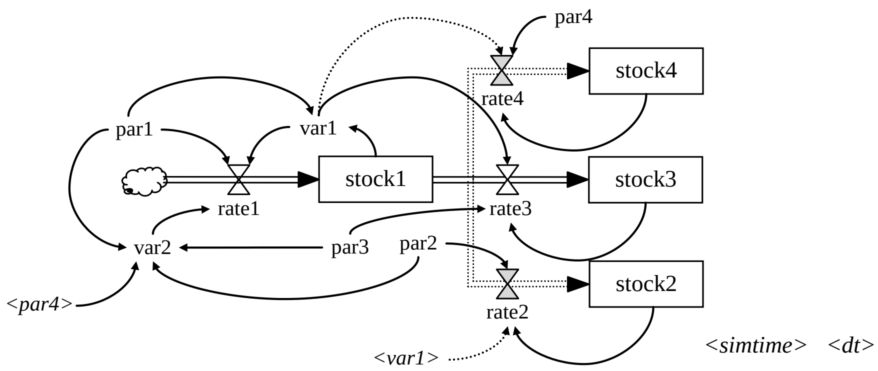


Figure D- 2: Dynamic hybrid modelling: 'SD agent flows'

Melhuish, Pioch and Seidel (2009) explore the concept of switching the internal decision making capabilities of agents; between reactive and proactive methods for decision making. They use this technique to explore simulation outcomes for counter-insurgency modelling. This concept could be implemented using some combination of the 'agents with rich internal structure' design concept and 'SD agent flows' within a dynamic hybrid modelling construct.

There are, therefore, a number of examples where the concept of 'dynamic hybrid models' are suggested but no research has been presented that specifically consider this class of hybrid design. This annex serves only to outline some initial thoughts that could be developed further.