A Critical Review of the Criticisms of System Dynamics

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Abstract

This paper presents a review of the criticisms of system dynamics and assesses the validity of these against recent findings in the field. The authors survey the literature critical of system dynamics and review their criticisms using the current understandings in the system dynamics field. This work suggests that there are some pertinent criticisms that have been aimed at system dynamics. These include the apparent disagreements regarding the role of historical data in model confidence building, system dynamics' reductionist perspective and how system dynamics addresses plurality and hierarchy. Overcoming these criticisms require the ever present need for education, communication and theoretical work. It is hoped this paper will strengthen the mandate of system dynamics in the eyes of its critics, assist and improve the field and its general acceptance as a tool of analysis.

1 Introduction

It is important that a field of research address its criticisms in order to understand, and help others to understand, its limitations, to strengthen the field of research and improve its general acceptance. Either by rebutting a criticism or redefining it in light of a well founded criticism, theories become stronger, more robust and it improves their chances of being accepted by a more general audience.

This paper is a review of some criticisms that have been levelled at the field of system dynamics and explores the field with respect to these criticisms. The paper will take an detailed look into several criticism, evaluate their validity and evaluate the measures that have been taken by academics and practitioners within the field to address the criticisms.

To build a critical analysis of the paradigm of system dynamics, we must understand the context of the field. System dynamics is a 'means of inquiring into the behavior of part of the world in order to understand it and hence indicate ways of improving its performance'. (Keys, 1990, p.480). The paradigm is one of many fields that can be used to try to understand the complex nature of the systems in which we work. System dynamics has roots and relationships with a number of diverse fields, including: systems thinking, servo-mechanism theory, dynamical systems theory, cognitive science and history (Richardson, 1991; Sterman, 2000; Meadows, 2008; Newell, 2012).

This paper is specifically looking at criticisms of the fundamentals of the system dynamics paradigm and not specific criticisms of technique, specific content theories of system dynamics or how these criticisms apply to other approaches often used instead of system dynamics. For example, Rouwette *et al.* (2011, p.1) claim there is 'no clear evidence for the effectiveness of group model building, and a conceptual model linking elements of the modeling process to goals is missing'. This is a flaw in a technique used in system dynamics, not of the whole paradigm itself and as such possible 'gaps' like this will not be included in the analysis. The later exclusion, that of other approaches, could prove a valuable extension to the body of systems research, but is precluded from this paper.

This paper's main contribution to the field of system dyanmics is to gather and review many of the criticisms that have been made of system dynamics. During the life of the paradigm, system dynamics has been the focus of a number of criticisms. However, there have been few attempts to bring a large number of the criticisms to bare together and assess them as a collective. This paper aims to bring many of these criticisms together and use the literature and an understanding of the paradigm to address them, identify which are valid and identify those that remain unaddressed.

This paper is also designed to stimulate discussion and more constructive criticism of system dynamics. System dynamics is a field that is not widely taught in schools and colleges (Forrester, 2007). As a non-pervasive field in education, it is possible that many critics of the paradigm would ignore it rather than prepare and deliver structured criticisms. It is hoped that this paper will stimulate critical debate of the field to compensate for a possible lack of enthusiasm from its external critics.

This paper will deal with five 'groups' of criticisms. These are listed below. Many of the 'areas' of criticisms contain an array of different criticisms that have been grouped to deal with common elements simultaneously. There are many common theoretical threads and challenges for the field that link the groups of criticisms, which will be brought out in the critical review and highlighted in the final discussion.

1. Applications of system dynamics
2. Mimicry of historical data and validation
3. Complexity
4. Determinism
5. Hierarchy

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2 Applications of System Dynamics

One of the more prolific areas that generate criticism is not of the paradigm itself per se, but are criticisms of how system dynamics has been applied. These criticisms of the application of system dynamics come from people from within as well as outside the field. These criticisms range from system dynamics being applied to the wrong situation to criticisms of particular models' complexity, layout and size (Forrester, 2007; Barlas, 2007).

It can be difficult to find published examples of poor applications of system dynamics. This is generally for two reasons. Firstly, many are not published. With the peer review process in many journals, poor applications of system dynamics, like poor journal articles, are rejected. The second reason is that for a model to be bad, someone analysing the model must know the system well and either analyse the proposed model to find its flaws or be able to prove how the assumptions or relationships within the model are fallacious.

2.1 Reasons for drawing criticisms

There seem to be four main reasons for these modellers drawing criticisms, many of which are covered by Forrester (2007) and Barlas (2007). Firstly, many of the examples of system dynamics that generate criticism are because system dynamics was applied to the wrong 'type' of problem (Forrester, 2007; Barlas, 2007). System dynamics is designed to explore 'problematic behavior patterns caused primarily by the feedback structure of the setting' (Barlas, 2007, p.470). Often however, system dynamics is applied to problems where exogenous influences drive the system. In the words of Barlas (2007, p.470) 'many so-called SD [system dynamics] modeling projects are about problems that simply do not have SD [system dynamics] characteristics.'

Secondly, some modellers just apply system dynamics incorrectly. System dynamics provides a set of tools and techniques to apply to the appropriate problems (as outlined above). However, some modellers misuse and mismanage the tools of system dynamics. Forrester (2007) and Barlas (2007) site the cause of this being the inherent difficulty of learning and applying the concepts of system dynamics. A claim supported by Cronin *et al.* (2009) and Sterman (2010) and their work with the understanding of the fundamental system dynamics concept of accumulation. Forrester (2007) and Barlas (2007, p.469) also site 'no formal/clear accountability for poor modeling' as a possible cause of inexperienced modellers publishing models that apply system dynamics incorrectly and flout many of the paradigm's rules and limitations.

Some people also have a different concept of what system dynamics is. As a group of theories and techniques, system dynamics can be seen as just a name applied to techniques and a process used to produce models. As a consequence, a modeller can call a process system dynamics in situation where others would not agree. Equally, someone observing a model can call the process used to get there system dynamics, even if it was not employed by the modeller. An example of this is Hayden's (2006) criticism of a model by Boyer (2001) that purports to define system dynamics' views on constitutional order, institutions, organisations and conventions. Radzicki & Tauheed (2007), question whether Boyer even proposed the model reflected the view system dynamics took to these facets of a system or even if it reflected anything of system dynamics at all.

Finally, the tendency to build unnecessarily large models to address 'big' problems is another aspect of modelling that draws criticism (Forrester, 2007; Barlas, 2007). Barlas (2007, p.470) explores several reasons why large models is an issue, stating that large models 'are not only difficult to build, they are also nearly impossible to understand, test, and evaluate critically'.

Both inexperienced and experienced modellers draw criticisms for their applications of system dynamics. Many instances where system dynamics has been applied poorly are done by practitioners with little system dynamics experience or those that are learning; we, for instance, have several examples that belong to that group. These tend to be of poor quality and Barlas (2007, p.469) notes that there are 'too many system dynamics models - published or applied - that do not meet our minimum standards of quality'.

However, some more experienced modellers also draw criticisms for their applications. Solow (1972), Marxsen (2003) and Simon (1981), for example, criticise Meadows *et al.*'s (1972) results published in the book *Limits To Growth* (also see Schmandt, 2010). Many of the criticisms of Meadows *et al.* (1972) were aimed at the different assumptions about the real world, some of which were clarified in the subsequent updates of the study (Meadows *et al.*, 2004; Meadows *et al.*, 1992). Others, such as Simon (1981), had fundamental differences in assumptions, which lead to the study drawing his criticism.

Other criticisms, founded as they may be, do not apply to system dynamics because they miss some of the basic theories and limitations of the methodology. For example, criticisms of models' inability to perfectly simulate reality, miss the point that models are often simplifications of reality used to understand behaviour modes. As Meadows *et al.* (1972, p.21) wrote "The model we have constructed is, like every other model, imperfect, oversimplified, and unfinished." These simplified and often unfinished works are therefore difficult to compare to historical data, a point discussed at greater length in the next group of criticisms.

2.2 Regressing the Problem and its Implications

To regress the problem of why there are poor applications of system dynamics only brings us to some well understood ideas within the field. The reasons for system dynamics being applied poorly and for people to fall victim to the reasons mentioned above are few, succinct and commonly known: the phenomena that system dynamics tries to explain are counterintuitive and training is needed for people to master the field (Forrester, 1961; 1971b; Cornin & Gonzalez, 2007; Cronin *et al.*, 2009; Sterman, 2010). However, there is one more aspect that this research does not appear to cover: they demonstrate a poor understanding of the field of system dynamics.

This analysis draws us to two points. Firstly, that there are examples of and many reasons for poor applications of system dynamics, some of which quiet rightly draw criticisms and some that should. Secondly, that there are misplaced criticisms on models that meet high quality standards in the field of system dynamics. These problems were the cause for Forrester's (2007) call for greater (more & better) systems education in schools and universities and for greater promotion of system dynamics in the public sphere.

Note will also be made here of a criticism put forward by Hayden (2006, p.534) that to my understanding has not been addressed in other literature. Hayden criticises the generality and unclear terminology used in system dynamics and its models. Further education of people outside of the field of system dynamics in the terms used in the paradigm could help to address this. Criticisms in this area help to illustrate how important further promotion and education in system dynamics is for the paradigm.

3 Mimicry, Validity, Comparison & Prediction

The inabilities of models to mimic reality and predict the future are common criticisms levelled at system dynamics (Solow, 1972; Simon, 1981; Keys, 1990; Hayden, 2006). Meadows *et al.*'s (1972) Limits to Growth provides an example of this. Many critics, such as Simon (1981) and Solow (1972), picked up on attributes of the model that lead them to believe the model did not reflect reality, disenchanting them towards the entire model and the conclusions that were drawn from it. What was lost however, was that the basic dynamics of the model still appear correct today, regardless of its inability to reflect exact points in historical time or to reflect the material wealth of the world today (Meadows *et al.*, 2004). Furthermore, if reflecting history is not necessarily a requirement of the field, then how do people know if the model is an accurate explanation for the underlying behaviour? This reflects a group of damaging criticisms that have been levelled at the system dynamics paradigm: models not mimicking reality, comparisons of models and reality, model verification and the dependence of the paradigm on data.

3.1 Mimicry

Many criticisms of system dynamics are aimed at the inability of the paradigm's models to mimic reality (Solow, 1972; Simon, 1981; Keys, 1990; Hayden, 2006). However, it is relatively widely accepted within the field of system dynamics that models are not designed to and cannot perfectly imitate the real world (Sterman, 2000; Forrester, 2003; Lane, 2000). As such, to get a model that reflects the actual system perfectly is not the goal of system dynamics.

Instead, the goal of modelling in system dynamics is to assist people to understand the internal systemic structure of a system that drives behaviour (Forrester, 1961; Senge, 1990; Sterman, 2000). Forrester (1985) and Radzicki and Tauheed (2007) even propose that the process of generating the model and learning about the system could even be of more benefit than the model itself. Their justification is that the process of modelling promotes greater learning about the internal causes and effects of systemic structure than the model on its own would.

Criticisms of system dynamic's tendency not to mimic reality appear to come from one of two areas. Firstly, from the point of view that system dynamics is a 'hard' systems thinking perspective (Keys, 1990). Hard systems thinking approaches, such as systems engineering and systems analysis, tend to

operate in environments of low complexity and high problem visibility. As a consequence they are designed to mimic historical data very closely. System dynamics however, is applied in situations of high complexity (with varying degrees of problem visibility), making it standout as a field that 'doesn't work' because of the often inability for model's inability to mimic historical data. Another possible reason for its apparent separation from other 'hard' systems methodologies is that because of its endogenous focus it often does not exhibit the behaviour caused by external shocks without the cause for the shock being explicitly included in the system.

The second reason arises from poor understandings of the goal of system dynamics: not to mimic or mirror the real world but to use models to understand why certain behaviour is occurring (Forrester, 2007; Radzicki & Tauheed, 2007). This again arises from system dynamics not being understood more widely. System dynamics is one of many fields that tries to make sense of a complex environment. It does not propose to uncover all there is to know about a system and like the other techniques it has its own goals, limitations and expected outcomes.

3.2 Model Verification and confidence building

Despite much of the learning coming from the modelling process rather than 'the' model, models are still an important part of communicating conclusions and testing their 'validity'. A model itself however, cannot be tested for validity. In fact, the idea of verifying a model is fallacious (Sterman, 2000). As Sterman (2000) points out, 'no model can be verified. Why? Because all models are wrong...... all models, mental or formal, are limited, simplified representations of the real world'.

Many researchers believe that building confidence in models is the central method of verifying a model (Radzicki & Tauheed, 2007; Sterman, 2000; Forrester & Senge, 1980). Confidence building in system dynamics is a method of verifying a model 'along multiple dimensions' (Radzicki & Tauheed, 2007). Sterman (2000) points out that Popplerian philosophy tells us while we can't establish if a model is correct, we can establish that a model is false. We can then alter the model to form a modelling version of an *auxiliary hypothesis* which we can then test. By subjecting models to a series of tests we can slowly build confidence in it: the more tests it passes the more confidence we have that the model reflects the correct behaviour. Peterson (1975, Appendix B) provides thirty-five informal tests that models can be subjected to build confidence. Similarly, Sterman (2000) provides ten such tests.

However, testing a model against historical data is still important for some modellers. For some, consultants in particular, comparing a model to historical data is the most important test of the model (Homer, 1997). For others, comparing the model to historical data is still considered one of the tests for building confidence (Sharp & Price, 1984; Sterman, 2000). One of Sterman's (2000) ten tests is the

Behavior Reproduction Test, which compares the model's numerical behaviour to past data (while at one point qualitative behavioural testing is proposed, Sterman does not discuss this point any further). However, Sterman (2000) does state that fitting the data does not mean validation and that the Behavior Reproduction Test is to uncover flaws and structural issues with the model.

Sterman's (2000) focus on historical data (a decent portion of the section dedicated to model testing) seems to differ somewhat with some other system dynamicists. Forrester (2003, p.5) claims that 'the dynamical character of past behaviour is very important, but the specific values at exact points in historical time are not'. Barlas (2007) supports this by purporting that 'proper measures of historical fit would stress fitting past dynamical patterns, such as periods, amplitudes and trends' (p.471). Keys (1990, p.488), after some discussion concludes that, 'model validity should be assessed relative to the purpose and not to a universal measure of correctness'. All of these appear to contrast with Sterman's (2000) *Behavior Reproduction Test*, which mostly espouses 'fit'. Even when there is only a variation in the bias equation (U^M) of Theil's Inequality Statistic, Sterman (2000, p.876) still claims that a systematic error should be 'corrected by parameter adjustment'.

The disagreement over the role of historical data in model validation makes Forrester's (2001) claim that more work needs to be done in the field to establish methods of model validity still pertinent. Ultimately, Keys (1990, p.488) claim that models 'should be assessed relative to the purpose' is appropriate. It also seems generally accepted in the field that comparing a model to historical data is one of the least powerful methods for building confidence in the model (Forrester & Senge, 1980; Saeed, 1992; Radzicki, 2004; Radzicki & Tauheed, 2007). However, there must be a use for historical data in to building confidence in a model that is supposed to emulate it.

Perhaps one of the more significant and overlooked tests is the qualitative assessment and comparison of a model's behaviour with historical data. As stated earlier, Sterman (2000) recommends qualitative comparison, but does not draw out the point any further. Peterson (1975, Appendix B) offers several tests that use historical data, but only qualitatively compares the relevant behaviours (although some could progress towards quantitative measures, Peterson does not explicitly include this extension in his test). Qualitative tests such as these could be used to address Forrester's (2001) and Barlas' (2007) assessments of model data with general patterns of behaviour.

Some of the criticisms, mostly originating from the 'hard' systems thinking approaches, claim that system dynamics generates models that have trouble matching historical data (Keys, 1990). As has been shown, researchers in the field still disagree about the role of historical data in building confidence in a model. Many researchers appear to agree that matching historical data exactly is not the aim of system dynamics, but this seems to be a source of much criticism. It seems researchers in the field need to ensure their critics are better informed about the theories they espouse.

3.3 Prediction and Prophecy: Determinism

When grouping system dynamics with other 'hard' systems thinking techniques, a common accusation of the field is its determinism and the accompanying tenet that it can predict or prophesises the future (Ansoff & Slevin, 1968; Sharp & Price, 1984; Jackson, 1991; Lane, 2000; Forrester, 2001). Many people disagree with this proposed capability; indeed it makes many others feel uncomfortable.

The complexity in the argument comes from the partial adherence of system dynamics to 'hard' system methodologies. Determinism is often considered a characteristic of 'hard' systems thinking approaches (Checkland, 1978; Lane, 2000). For situations with low uncertainty and relatively low complexity, hard methodologies, such as cybernetics, have been employed to mathematically model the system to predict behaviour. As system dynamics adopts some of the characteristics of 'hard' systems thinking, many see this as also taking a deterministic view of the world. Many however, believe that system dynamics cannot be as deterministic as other 'hard' approaches because of the complexity of the systems it attempts to deal with. As Hayden (2006, p.539) states, 'Social systems are much too open, irregular, and dynamic for a mechanistic theory to apply' (this statement contains a variety of criticisms which will be decomposed gradually throughout the paper).

Forrester (1968) and Coyle (1986) counter determinism by arguing that system dynamics is concerned with the structure of the system under examination and the structural reasons for the broad behaviour of the system. These observations in isolation excludes the use of dynamic models to observe the implications of actions on systems, for example, in the Beer Game. This would encourage only setting a model in action and seeing where it tended to find equilibrium and not using it to test pulses or shocks to the system.

Perhaps Lane's (2000) invocation of Popper's (1945a; 1945b; 1957) view of determinism is more appropriate: 'prophecy is sharply distinct from that of 'technological/scientific prediction" (p.7). Popper (1945a; 1945b; 1957) defines technological/scientific (here on scientific) prediction as being conditionally dependent on the assumptions; if one of the assumptions changes then the prediction becomes invalid. From a system dynamics perspective, models and any of their predications have similar limitations. Lane (2000) even draws attention to early writing in system dynamics, (such as Forrester, 1961) to demonstrate that a deterministic view was never really espoused by the field. Perhaps such a description may not even apply to many of the so-called 'hard' systems thinking approaches.

Forrester's (1968) and Coyle's (1986) views are not necessarily divergent to Popper (1945a; 1945b; 1957) and Lane's (2000). Understanding the system is one of the main goals of system dynamics, key to Forrester's (1968) and Coyle's (1986) counterarguments. It is beyond understanding the current structure and cause of behaviour and into scientific prediction, where the dynamic aspect of assumptions and conclusions are more uncertain, when Popper's (1945a; 1945b; 1957) and Lane's (2000) counterarguments becomes important.

3.4 Tipping points

A note can be made here about the idea of tipping points. Both Sterman (2000) in his explanation of the Susceptible-Infectious-Recovery (SIR) model and Morecroft (2007) in his explanation of models of fisheries, use the term tipping point. Tipping point in these instances refers to the shift from one feedback loop being dominant to another and a shift in the behaviour of the overall system and Sterman's (2000) and Morecroft's (2007) examples demonstrate that the techniques used in system dynamics are capable of simulating these shifts.

However, there are other shifts that system dynamics may not be able to simulate as well. As shown above, system dynamics is only a methodology of scientific prediction, limited by the assumptions made in 'foreseeing' the implications of action taken on the system. Sometimes an event or change may occur in the system that results in new feedback loops forming and becoming dominant; a shift in the structure of the entire system. Often, revisiting a model, like one does with their mental models, is the only way to understand a change in system structure, though this often occurs in retrospect of the structural change.

Perhaps scenarios could be helpful to simulate these structural shifts. 'Scenarios' have been used to simulate shifts in parameters and observe their effect on the resulting systemic behaviour (Zagonel *et al.*, 2011). These can simulate possible shifts in feedback loop dominance within a system before the event occurs (Morecroft, 2007; Sterman, 2000). However, the situation is different when addressing a shift in the structure of the system. Maybe scenario planning, that envisions entirely different system structures and not just scenarios in the form of parameter variations, could be used to build a methodology that considers these potential structural shifts and uses system dynamics to help understand potential systemic behaviour.

3.5 Implications

These criticisms are damaging for system dynamics as they negatively affect general opinion of the field and its validity. By demonstrating that the model upon which conclusions are drawn does not reflect historical data, people who aren't versed in the particular theories and limitations of system dynamics begin to believe that the field offers little value. That is, if people believe that system dynamics tries to mimic and even predict the real world, and are shown that model that are proposed as system dynamics models do not do this, then they may tend to believe it is the paradigm at fault and not the criticism of prediction itself.

4 Complexity: Richness, Reductionism, Pluralism & Social Systems

From a 'soft' systems perspective, it is argued that the dependence of system dynamics on quantitative data and explicit relationships does not allow system dynamics to deal with the complexity of the real world and reduces the richness of analysis it can conduct. (Keys, 1990). 'Soft' systems thinking and approaches often deal with more complex environments than 'hard' systems thinking (Checkland, 1978; Jackson & Keys, 1984). To deal with this complexity 'soft' systems thinking relies on qualitative information and linguistic terms to describe complexity (Checkland, 1978; Keys, 1990). Many believe that this level of detail cannot be caught by the hard data and mathematical models that are used in system dynamics.

In reply to this criticism, Keys (1990, p.489) argues that '[t]he use of causal loop models is a movement towards the soft systems type of model but the reliance upon a single model remains a basic difference between [system dynamics] and soft systems methodologies'. This counterargument only goes some of the way to answering to the criticism.

Perhaps a better approach to addressing this criticism is by emphasising that the model itself is only a portion of what the system dynamics proposes it can do. As stated earlier, system dynamics is essentially a learning tool and the 'process' of modelling is often seen as more important than the model itself (Forrester, 1985). The process of modelling involves information transfer of a rich linguistic and qualitative nature that 'soft' systems proponents believe system dynamics lacks. Moreover, it assists the field to deal with increasingly complex situations, similar to those addressed by 'soft' systems thinking.

4.1 Reductionism

System dynamics has often been accused of being reductionist (Keys, 1990). Reductionism - the act of describing a system through only discussing the interactions of its parts - has generally been deemed inappropriate for social messes (Ackoff, 1974). 'Hard' systems theories use reductionism to create laws and rules that define how the system operates (Keys, 1990). 'Soft' systems methodologies however, which are designed to deal with social messes, do not take a reductionist perspective (Jackson, 1982). As system dynamics appears to break down the system to understand how its components interact - essentially using reductionism - many perceive system dynamics as unable to deal social messes (Keys, 1990).

Rather than these criticisms taking issue with the reductionist nature of system dynamics - the breaking down of the system into nodes in a model - the issue seems to be with using these nodes to construct the system that simulates the behaviour under examination. However, the 'reductionist' criticism assumes that a reductionist hypothesis implies a constructionist hypothesis, an assumption disproved by Anderson (1972).

The constructionist criticism is however, harder to disprove. Anderson (1972, p.393), states that the 'constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity'. However, it is sensible to conclude that in many situations a limited increase in the scale and complexity can allow one to construct the system out of the basic theories, just as Newton's theories of mechanics can be used to construct Kepler's laws of motion. As Anderson (1972) points out, to do this, one must have an understanding of the functionality, structure and goals of the 'higher hierarchical' system (or theory, as is the case in the above example).

System dynamics essentially does just this. It uses complex basic principles to describe complex systems. However, constructing the system, or rather a model of the system, from these principles requires an understanding of the structure of the system in question, precisely where the paradigm proposes to start. Furthermore, as outlined above, the techniques involved in system dynamics can only be applied to the 'right' type of problem. While it seems clear that more work needs to be done on the theoretical foundations of system dynamics in this area, it is apparent that part of the notion of 'the' right problem is one that can be analysed using the right amount or types of reduction.

4.2 Pluralism

The notion of pluralism affects two distinct acts in system dynamics. Firstly, in the form of multiple perspectives of the complex decision problem, the goals of system intervention and different perspectives of the system itself. Secondly, pluralism in the way individuals behave differently within a system.

System dynamics, as Forrester (1961; 1969; 1971a) defined it and its approaches (otherwise known as Forrestarian system dynamics - the system dynamics of M.I.T. in the 1960's and 1970s), is accused of not dealing with pluralism (Keys, 1990). What 'type' pluralism Keys (1990) is referring to is not immediately evident. However, when referring to 'hard' systems thinking, Jackson & Keys (1984, p.476) state that '[a] set of decision makers is pluralist if they cannot agree on a common set of goals and make decisions which are in accordance with differing objectives.' That is, 'Hard' systems methodologies do not consider a range of perspectives on goals, 'the' problem or 'the' system offered by the relevant people. The idea that multiple perspective should be considered is known as weltanschauung, a term used frequently by Checkland (1981; 1987).

If this is the 'type' of pluralism Keys (1990, p.485) is referring to then it seems he believes that Forrestarian system dynamics makes no greater attempt to deal with plurality of perspectives as any other 'hard' systems thinking approach. However, Keys (1990) sees the introduction of influence diagrams into system diagrams in the 1980's, by a group at Bradford University, as a significant step towards dealing with pluralism (see Wolstenholme, 1982; 1983; Coyle, 1983; for a brief history of causal mapping see Sharp & Price; 1984). Keys (1990) believes these diagrams allow system dynamics to accommodate many perspectives on 'the' goals of intervention, the problem and the system in question.

More recently techniques, such as Collaborative Conceptual Modelling (CCM) developed by Newell *et al.* (2008), Newell & Proust (2009) and Newell *et al.* (2011) further allows system dynamics to accommodate pluralism. CCM uses a collaborative approach whereby people map out their own perspectives of the systems and then slowly build on this with other stakeholders or 'relevant' people to come to a broad agreement on the structure of the system. Processes such as these can however, be politically charged and it is the responsibility of the system dynamicist to negate any of the possible negative consequences that such processes can entail.

Pluralism seems to be slowly being addressed by the system dynamics paradigm. However, it seems that more work needs to be done to ensure plurality is considered. In situations where problems and system structures are hard to define (wicked problems, Churchman, 1967), it is important that people do not become subject to group think or narrow avenues of thought in order to properly identify the goals and system structures and assist the adoption of any recommendations offered (Größler, 2007).

From the perspective of a plurality of actors within the system, system dynamics has the ability to model at an aggregated level right down to the individual level. Osgood (2009) states that while many studies are aggregated (gives many example), some dynamics models need to model individual behaviour. The level of detail depends on the purpose of the model and the implications of individual behaviour. Osgood (2009) proposes a model to assist with modelling individual's behaviour in a more effective way, bridging the gap between aggregation and individual modelling and assisting system dynamics to consider plurality. However, as simpler models are easier to understand it is important that the correct level of aggregation is selected.

4.3 Social Systems: 'Open, irregular & dynamic'

One of Hayden's (2006) central claims against system dynamics is that the social systems that system dynamics attempts to explore are 'much too open, irregular, and dynamic' and states that cybernetics - a very mechanistic approach of analysing systems - is far to structured to deal with such complexities (p.530). To explore this criticism, it will be broken down into its components, beginning with the proposed link between system dynamics and cybernetics.

Cybernetics

In their critique of Hayden's criticisms, Radzicki and Tauheed (2007) refer Hayden to the work of Richardson (1991). Richardson (1991) takes an in depth look into the history of feedback thought in both the social sciences and systems thinking. He identifies 'two main lines of development of the feedback idea.... the servomechanisms thread and the cybernetics thread' (Richardson, 1991, p.1). Richardson (1991) explicitly places the system dynamics 'tradition' in the servomechanism thread (see Richardson 1991 for more on the servomechanism theory and system dynamics).

Open

Many social systems are open and subject to outside influences. Hayden (2006) claims that system dynamics cannot model this apparent openness in these systems and on this point it appears theory in the field supports this claim. System dynamics does not attempt to model the effect of external behaviour on a system, instead it addresses the behaviour generated internally by a system; that is, it takes an endogenous view of behaviour. It is the internal behaviour of a system that often drives the system (Forrester, 1961; Senge, 1990). Richardson (2011) believes that it is this endogenous perspective that is the fields greatest contribution to the study of systems. This endogenous view was behind one of the first applications of servomechanism theory to economics, conducted by Goodwin (1951).

The endogenous perspective may be confused somewhat by comments such as 'in reality flows are determined by so many external things' (Hayden, 2006, p.534). When taken out of context, Sterman's (2000, p.95) claim that 'the focus in system dynamics on endogenous explanations does not mean you should never include any exogenous variables' could add to the confusion. However, as Sterman (2000, p.95-6) clarifies, 'the number of exogenous inputs should be small, and..... carefully scrutinized to consider whether there are in fact any important feed feedbacks [involving the exogenous input]'. This is how Sterman (2000) justifies the ability to use historical data in some sense to test a model: without any external inputs, the model's behaviour may be completely different to the behaviour of the actual system.

Irregular

Social systems appear irregular. However, driving humans' behaviour is a system of rules, obligations, controls, regulations and limitations that is defined by them. This appears to be a deterministic view, but as outlined earlier and by Lane (2000), this view is not deterministic as it integrates the 'agency and structure' that is common in many contemporary social theories.

When taking this view is seems many of the irregularities are removed. However, external factors still play a large role in determining the behaviour of the system. Take, for example, the Beer Game (Senge, 1990); the Beer Game begins with a shock to the system, without which the behaviour commonly observed in the game would never take place. This is where the internal focus of system dynamics is important. Once the internal system architecture is understood and the shock that caused the real behaviour is understood, in an appropriate application of system dynamics, the behaviour of the system is dictated internally after the shock.

This perspective is supported by much of the thinking on mental models - the mental constructions we have of the real world. Real systems can be very complex and humans often have difficulty accurately identifying the causes of certain systemic behaviours due to factors such as time and spatial separation of cause and effect and incorrect or limited information (Piaget, 1928; 1930; Sterman, 2000; Sosna *et al.*, 2010). Consequently, what may appear irregular is actually not, it is just the inability of humans to properly attribute cause, the appearance of cycles and apparent inconsistencies.

Dynamic

Hayden (2006) also believes that system dynamics cannot deal with the dynamic nature of social systems, but does not elaborate further on this point. Much of a social system's dynamics stem from the irregularities and openness of the system. Both of these characteristics can cause a system to fluctuate so much that would be difficult to understand the underlying causes and patterns in the behaviour. However, as has been shown, system dynamics uses limited openness to understand the exogenous nature of the system. By limiting its scope, it is providing a perspective that could help explain the dynamic characteristics of the system. Furthermore, irregularities in the system are often only apparent irregularities with many suggesting that there is an underlying order, as has been shown in the Beer Game (Senge, 1990).

A different perspective on the criticism is that Hayden (2006) believes that system dynamics cannot handle dynamics or explore dynamic behaviour. As the goal of the paradigm is to understand dynamic behaviour and as dynamicists have provided many examples that the tools of the field do handle and explore system dynamics, this seems unlikely (Forrester, 1961; for examples of system dynamics see references). However, without any further clarification of Hayden's (2006) criticism, further discussion on this point is likely to yield little.

5 Determinism: Dehumanising, 'Grand' Theory and Austere

Somewhat linked to the previous discussion of determinism from the point of view of prediction and prophesy, system dynamics has also been accused of being deterministic in the sense of dehumanising, aspiring to be some 'grand' theory of systems and operationally austere (Jackson, 1991; Lane, 2000). These differ from determinism as it was previously discussed as the criticisms relate to an accused imposition of system dynamics on humans and theories. These are still considered as deterministic attributes however, because these criticisms still imply the human aspect of systems research be somewhat removed. Grand theory is placed here because of its apparent disregard for the variation between systems, particularly from the human perspective.

5.1 Dehumanising

Jackson (1991) believes system dynamics is deterministic and that it relegates people to 'cogs in a system' and disregards free will. Many instances of such criticisms view system dynamics making the assumption that laws operate outside of human subjectivity and of dehumanising its topic (Lane, 2000). Lane (2000) sites Forrester (1961) and Bowen (1994) to demonstrate that system dynamics is not as deterministic as Jackson (1991) believes. As a detailed analysis is given by Lane, only a brief account of the counterargument will be given.

Forrester's view is that system dynamics takes the perspective that 'decisions are not entirely "free will" but are strongly conditioned by the environment' (Forrester, 1961, p.17). Furthermore, system dynamics is designed to allow people to recraft a system advantageously and promote different behaviour, thereby acknowledging the actual environment that 'conditions' people's behaviour (Lane, 2000). Bowen's (1994) take on the topic is somewhat similar, believing the ability to change the system structure and the conditions of decisions places system dynamics on a middle point of human determinism. This is somewhat supported by Bloomfield (1982), who demonstrated that system dynamics is described by neither complete determinism or complete free-will.

However, Lane (2000) believes that this 'mid-point' between deterministic and complete 'free will' is an unsatisfactory conclusion. Lane (2000, p.10) recommends that more contemporary 'social theories which integrate agency and structure by giving an account of the process that mutually shape them both' is a more appropriate lens through which to observe the paradigm's treatment of human action.

5.2 System Dynamics as a 'Grand' Theory

A second aspect to the determinism criticism of system dynamics is that it is proposing a form of a 'Grand' theory. The idea of a 'grand' theory is not unknown in science, for example Von Bertalanffy's (1968) General Systems Theory (GST). These 'grand' theories proposed to bring together 'models, principles, and laws that apply to generalized systems... It seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to systems in general' (Von Bertalanffy, 1968, p.32).

However, system dynamics is only a methodology applied to different situations and does not promote a single 'Grand theory' of systems (Lane, 2000). While this does fit, for example, within one of Von Bertalanffy's (1968) domains, it still removes the notion of universally applied concepts and principles of General Systems Theory and other 'grand' theories.

5.3 Austere

Another perspective on the deterministic nature of system dynamics is given by Jackson (1991), when he groups the paradigm with that of systems engineering and systems analysis. Jacksons (1991, p.80) criticism of the group is that 'people are treated as components to be engineered just like other mechanical parts of the system. The fact that human beings possess understanding and are only motivated to support change and perform well if they attach favourable meaning to the situation in which they find themselves is ignored'.

To address this criticism, Lane (2000) explores the idea that 'system dynamics has an austere view of what should be in a model and coercive view of how users should respond to such a model' (Lane, 2000, p.15). He explores the multitude of views considered by system dynamics, the multiple possible objectives of system dynamics, relationship between modeller and problem owner and the fallacious idea of using system dynamics to search for an 'optimal solution' (Lane, 2000).

The idea that Jackson is referring to the operational austerity of the process seems only part of the criticism made by Jackson. Lane (2000) demonstrates that in the execution of the techniques of system dynamics, understanding and motivation are considered. It seems just as likely though, that the criticism is aimed at the understanding and motivation of people within the system being explored. These notions are addressed by system dynamics in such elements as the 'modes of behaviour' the paradigm wishes to explore and goal seeking activity (Forrester; 1961; 1969).

6 Hierarchy

Hayden (2006) makes three direct criticisms of system dynamics all with regards to a figure purported by Boyer (2001) (see Figure 1). One of the criticisms was with regards to system dynamics and its consideration of hierarchy. Radzicki and Tauheed (2007, p.1) address this criticisms by demonstrating that Boyer's figure is not intended to describe how system dynamics considers hierarchy. Radzicki and Tauheed (2007, p.1) go further by explaining that the non-linear nature of system dynamics puts limitations on the systems that the methodology deals with and that these limitations describe are the systems hierarchy. This explanation appears to be only part of how system dynamics considers hierarchy, but before we go further, a brief exposition of hierarchy is needed.

Checkland (1981) sees 'emergence and hierarchy, communication and control' as 'basic' systems ideas and central to understanding a system's behaviour. Hierarchy, in Checkland's sense, is the relationship sub-systems have to each other (Checkland, 1987). The hierarchy that forms in a system defines a set of rules, obligations, controls, regulations and limitations that exist within the system (Hayden, 2006). To address is criticisms, system dynamics should have a clear picture of how it's techniques consider and inform users of these features of hierarchy.

Techniques in system dynamics, such as influence diagrams and causal loop diagrams address the rules, obligations, controls, regulations and limitations to a certain degree by outlining the structure of the system and linking relationships between elements of the system. However, they do not describe much about the relationship between the elements of the system as, because these are simplified reflections of peoples' mental models, they are not designed to.

It is not until a dynamic model is built that the rules, obligations, controls, regulations and limitations are formalised and crystallised to reflect the system. These models define the rules, obligations, controls, regulations and limitations within the model by mathematically defining the relationships between elements.

These arguments only scratch the surface of the question of hierarchy in system dynamics. Radzicki and Tauheed's (2007) contribution is that the nonlinear nature of system dynamics places some of the limiting factors on systems explored by system dynamics. Here it is argued that the modelling of systems and the relationships outlined in those models contain many more of the 'rules, obligations, controls, regulations and limitations' in the system and that modelling plays a greater role in addressing hierarchy. Perhaps hierarchy, and maybe Checkland's (1981) other 'basic' system ideas, need to be discussed application by application to ensure their consideration in modelling, or perhaps system dynamics needs to crystallise its thinking in this area and construct formal theories around system hierarchy.

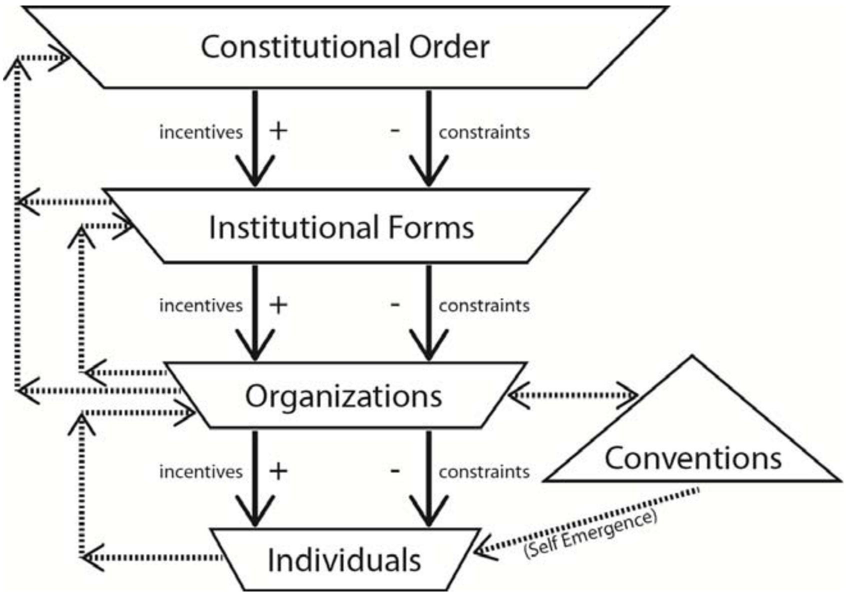

Figure 1: Hierarchy: Rules and Relationships between Constitutional Order, Institutions, Organisations and Conventions (Source: Boyer, 2001)

7 Discussion

7.1 Communication

As was shown in the above review, while many of the criticisms that have been aimed at system dynamics are theoretically founded, many are invalid in the context of system dynamics. These demonstrate more a poor understanding of system dynamics rather than failures of system dynamics.

However, the concepts behind and encapsulated in system dynamics and can be difficult to understand and learn (Forrester, 1961; 1971b; Cornin & Gonzalez, 2007; Cronin *et al.*, 2009; Sterman, 2010). Furthermore, the conclusions reached through a system dynamics process and its models are often difficult to communicate to people not directly involved in their generation (Größler, 2007; Barlas, 2007). These pose great challenges for the field of system dynamics.

These errable criticisms exemplify the problem for system dynamics. It demonstrates that many people, including those willing to criticise it, have a poor understanding of the underlying theories of systems dynamics; in particular its aims, techniques and limitations. Overcoming this through communication and developing a greater understanding of system dynamics in a general audience is important for the field (Forrester, 2007).

Despite this level of aptitude in communication, some believe that system dynamics does have some intuitiveness in its communication. Sharp and Price (1984, p.5) believe that 'it would seem unlikely that policy prescriptions generated via SD [system dynamics] models would enjoy even their present success, if the reason for them working could not be appreciated by the decision maker in a straight forward way'. However, this view is concerned with the communication of results, rather than communication of the theories underpinning system dynamics, a different discussion that itself needs development (see for example Größler, 2007).

7.2 Adoption

Forrester (2007, p.361) stated that the 'failure of system dynamics to penetrate lies directly with the system dynamics profession and not with those in government'. System dynamics has been developed over fifty years and has been applied successfully to many situations: one must question why is it not in great use. Forrester (2007) later describes some of the exigent needs for the field, including education, increasing public awareness and promoting system dynamics as a tool that can be used to help solve some of their problems. The above review demonstrates that this call is still pertinent. Perhaps Ulli-Beer *et al.*'s (2010) model of acceptance (adoption) and rejection (abandonment) dynamics could provide more insight into how this could be achieved.

7.3 Critical review

The review has uncovered some exigent theories in system dynamics that need to be developed and consolidated. How to build confidence in models is one such area that was identified. There are several different theories in the field regarding confidence building that appear to conflict with each other. Contrasting theories that allow people to build confidence in different ways might be good for system dynamics if they are mutually accommodating. However, the different perspectives on confidence building, in particular the importance of historical data and how it can be used, can be damaging for the field as it gives external observers the impression that the paradigm is in its adolescence, with major theories still in contention. This could be a partial explanation for the low adoption rate of system dynamics.

System dynamics also has some criticisms that remain unaddressed. While individually system dynamicists can somewhat deal with the endogenous nature of system dynamics and the as yet unsettled debate on the use of historical data in confidence building, together they create some unease and do not appear to coexists. If historical data is important then the study of purely endogenous behaviour is diluted as external noise and pulses are required to mould the model to simulate historical data. If endogenous behaviour is the central aim of any application of system dynamics, as has been shown by Richardson (2011) and above, then comparison to historical data is likely to be one of the less useful tests for a dynamic model. A clearer understanding of this apparent inability to coexist or proof that it is not a dichotomy at all would be an valuable contribution to the field.

Hierarchy is another area that seems to have received little attention in the system dynamics literature. The argument above is that system dynamics builds into its models the rules, obligations, controls, regulations and limitations to which the term hierarchy refers. However, if hierarchy is one of the four 'ideas' central to understanding a system's behaviour as Checkland (1981) purports, then perhaps more developed and detailed work in this area is required. By establishing and addressing these more commonly accepted 'systems ideas' perhaps greater dialogue and exchange can begin to occur between the field of system dynamics and the larger field of systems research, something that others have observed have been lacking in the field (see Forrester, 2007).

The review has also uncovered theories that have been somewhat addressed, but a shortage of literature and research in the area suggests more work needs to be done to establish a strong theoretical position. For example, work is being done on pluralism from the perspective of differing points of views on the problem at hand, goals of intervention and the structure of the system itself (for example Newell *et al.*, 2008; Newell & Proust, 2009; Newell *et al.*, 2011). However, systems dynamics could draw on other pluralistic activities, such as those suggested by Sibbet (2010; 2011) or those used in Technology Roadmapping (Phaal *et al.*, 2010), to improve its ability to build consensus and consider multiple perspectives. Bounded rationality limits one's decision making abilities (Simon, 1953). By including more perspectives in the process and increasing the 'bounds' that limit the problem and potential adaptations (actions & reactions to the problem), the rational used to make decisions - and in the case of system dynamics learn about systems and test and develop mental models - can be improved and perceived limitations can be removed.

Another example of partially addressed theories is that of pluralism from the perspective of aggregation within the system. This tends to be addressed on a contingent, application-by-application basis. It can be difficult for people learning system dynamics to achieve an appropriate level of aggregation and often trial and error is required to do so. It appears the field could benefit from work being done to generate more formal and teachable rules for aggregation in system dynamic models.

One obvious conclusion that became clear in our search and review of the criticisms of system dynamics is that there are few criticisms aimed at the mathematics behind system dynamics. It is likely that this is because of the field's strong mathematical foundation in Dynamical Systems Theory, a branch of mathematics that has been around for hundreds of years and has its origins in the work of Isaac Newton (Beltrami, 1987). This strength of the field's is important and should not be lost in the process of addressing and developing the more qualitative and philosophical issues raised in this review.

7.4 Overcoming the criticisms

Calls for education (Forrester, 2007; Barlas, 2007) and calls for more theoretical work (Forrester, 2007; Lane, 2000) are two often cited areas that the field of system dynamics could develop to help overcome its criticisms. Developing the theories underpinning the field and informing people of its goals, techniques and limitations would help reduce invalid criticisms of system dynamics and build its theoretical resilience.

In addition to education and theoretical work, the review has identified an image issue for system dynamics. Bourne from poor education in the field, partially explained by its complexity, many seem to believe the field unready or unable to assist in dealing with the complex world for which it was designed. Whether it is because of its seeming unsettled validation techniques, its implicit handling of hierarchy, unconventional take on determinism and free-will, its adaptable take on pluralism or some other yet unidentified issue, applications of system dynamics seems to incur scepticism among many individuals. Despite positive reviews in many fields of the benefits of applying system dynamics and optimism of its potential, it is important system dynamics works to address the scepticism that it imbues.

8 Conclusion

System dynamics has two central problems that lead to many of the claims being made against it. Firstly, is that it is often misapplied (Richardson, 2011). Secondly, as has been shown in this paper, that people are often misinformed as to its goals, expected outcomes and limitations.

Central to the second point is the endogenous perspective, that many critics apparently do not understand or know, the encouragement of learning during the process of forming a model, and not the emphasis on 'the' model, and the contingent nature of its application. A possible cause of much of this miscommunication is people applying system dynamics incorrectly, not qualifying their applications appropriately, or overstating the outcomes from the process.

Systems dynamics also needs to address more formally some of the more considered criticisms of the paradigm. A formal understanding of how system dynamics considers hierarchy is one such example. Addressing the concern for complex applications and a more formal method of quantising intangible variables. Many of these criticisms could be the cause for the poor take-up of system dynamics in strategy and policy development (Größler, 2007; Forester, 2007). As a consequence it is important system dynamics address these issues, and all other criticisms, to strengthen the field, both theoretically and in the eyes of potential users.

Finally, system dynamics needs to have greater communication with the public, with other technical people and with other systems research areas (Forrester, 2007;

Barlas, 2007). Communication with the broader public could increase its adoption and help it to be utilised more broadly. Communication with technical people, other academics and other fields of systems thinking could help to develop the field's basic theoretical framework. Finally, greater communication is essential in educating people about system dynamics, which could help to avoid the errable and misapplied criticisms that have been aimed at system dynamics.

Many of the criticisms of system dynamics, such as its determinism and human austerity have been addressed. However, theoretical work still needs to be done on some of the field's criticisms, including the role of historical data in building confidence in models, the field's reductionist perspective and how system dynamics addresses plurality and hierarchy. Such work, combined with increased education and communication, would help the field to be accepted more broadly.

Further work could also be done to explore how these criticisms apply to other approaches that are used instead of system dynamics. Using criticism to compare different paradigms can prove valuable when selecting the most appropriate approach for modelling and problem solving.

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