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Decision Support

Towards a behavioural system dynamics: Exploring its scope and delineating its promise

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ABSTRACT

Attempts to examine so-called 'behavioural effects' have reached into many different fields and are in full sway across OR. This paper considers whether this can be applied to System Dynamics modelling in a useful way. The idea is that humans frequently do not employ strict rationality in their daily lives but make errors and are subject to fallacies. This can shed light on the cognitive and human interaction aspects of the process and outcomes of modelling. The paper first raises concerns about the current state of 'Behavioural OR' – BOR. To refocus the underlying ideas it then returns to the Decision Theory roots, takes a broader view using an illustration from the history of science and then builds on work which first proposed a link to System Dynamics (SD). The core of the paper then explores in depth how behavioural ideas apply to SD. This is done using examples dealing with complex systems in a 'naïve' versus a 'sophisticated' way, and then using a mind map. It then offers a new and detailed framework of the stages of an SD-based intervention, indicating the presence of behavioural effects and providing a fine-grained discussion of those effects as they apply to SD. It builds on this by proposing a definition of 'Behavioural System Dynamics' (BehSD) in terms of its perspective on phenomena, five new, constitutive axioms, and its potential for improving practice. The paper closes by reprising the nature and potential of 'BehSD' and by sketching how research that adopts this perspective might go forward.

1. Introduction

This paper is a methodological exploration which considers the research question, 'Can behavioural concepts be applied to System Dynamics modelling in a useful way?' The core of these concepts is the idea that humans frequently do not employ strict rationality in their daily lives but rather tend to make errors and be subject to fallacies and biases, and that they do so in a systematic and experimentally observable way. The 'behavioural turn' involves examining potential examples of these phenomena and seeking to explain them, and even reduce or remove their effects in order to improve outcomes.

This idea has influenced a range of disciplines, from Economics (exemplified in the works of Kahneman & Tversky, 1979 and Smith, 1962, Simon, 1955, Thaler, 1980) to Finance (see founding works of Shefrin & Statman, 1985 and de Bondt & Thaler, 1985) . It is a significant feature in the related area of Operations Management (see Katsikopoulos & Gigerenzer, 2013; Morrison & Oliva, 2018; Sterman, Oliva, Linderman, & Bendoly, 2015; Walker, Chicksand, Radnor, & Watson, 2015). Indeed, the production and operations management society (POMS) has a 'behavioural operations' college and a dedicated area in its journal. It can be seen implicitly at the core of simulation and agent-based modelling (e.g. Squazzoni, Jager, & Edmonds, 2014). The idea is also present in more distant fields, for example, Archaeology (Reid, Schiffer, & Rathje, 1975).

This interest is also an emerging trend in Operational Research itself. This paper was partly prompted by 'Behavioural OR', which in recent years has become a significant element in debates on OR methodology. This trend - Behavioural OR, or BOR – aims to shed light on the cognitive and human interaction aspects of the process and outcomes of modelling. It provides useful insights into theory and practice, particularly work emphasising 'group modelling' approaches and Problem Structuring Methods (PSMs). Here one can see the link with System Dynamics modelling (SD). SD uses mathematical artefacts, simulation models with roots in servomechanism theory and control theory (Forrester, 1960/1975; Towill, 1993). Use

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of these models aims to add structure to 'messy' situations and to support organizational thinking (Forrester, 1958b, 1960; 1961a; 1965; 1968b; 1971). Since this has always been its aim, it became possible to see strong methodological links with OR (Lane, 1994) and explain its increasing acceptance into the OR toolkit (Jackson, 2019; Mingers & Rosenhead, 2001). It therefore makes sense to use the disciplinary setting of OR as a departure point, to use the work on BOR – its strengths and its weaknesses - to inspire and to some extent shape our interest in exploring the potential of applying the behavioural turn to SD.

The BOR debate is in full swing. It is a vibrant presence at OR conferences and has generated papers, edited books and journal special issues, not least in EJOR (Franco & Hämäläinen, 2016a); including two recent papers reviewing work (Franco, Hämäläinen, Rouwette, & Leppänen, 2021; O'Keefe, 2016). Something noteworthy is happening. However, is this such a fine place to be? In our view there are issues regarding how BOR has emerged and how OR practitioners have responded.

In 2013 the UK OR Society supported a 'Fostering BOR' initiative. There was a feeling that BOR seemed useful – but little clarity about its benefits. A collection of responses appeared (Kunc, Malpass, & White, 2016) (a second followed: Kunc, Malpass, & White, 2020) and the ORS has a new 'special interest group' on BOR. A contrast was the 2014 OR conference. This had a plenary session on BOR. The experience was curious. OR56 attracted colleagues from academia, industry and government. The 'catholic' view of OR produced sessions and participants across the spectrum of OR from theory to practice; from highly mathematical to more qualitative / conceptual. A receptive audience for BOR? Yet the reaction was highly muted. Attendees felt that the insights on offer were nothing they did not already know; and they were unclear BOR could generate any new insights. That experience was clearly not unique: Brocklesby (2016)) addressed a BOR paper to; "members of the OR community who remain unconvinced …" (p. 796). Whilst this paper is convinced of the value of the behavioural turn, our attempt to apply it to SD demands some awareness of the uneven response to BOR and what we see as issues with current BOR thinking. We therefore take a critical look at the behavioural turn in OR before exploring what this perspective can offer SD. The paper proceeds as follows.

Section 2 voices some concerns with the behavioural turn in OR. Section 3 attempts to establish the core ideas of BOR, first by returning to its roots in Decision Theory and then by taking a broad view using an illustration from the history of science. Work which first proposed a key link between those ideas and SD is then reviewed. Using this re-focussing, Sections 4 and 5 explore the scope of applicability to SD. It then offers a new framework of the stages of an SD-based intervention and a fine-grained discussion of the behavioural effects that apply. Section 6 builds on this by showing how the framework can contribute to the application of behavioural ideas to SD. It then offers not a fully developed theory of 'Behavioural System Dynamics' (BehSD) but some axioms, foundation stones necessary to formulate one. The paper closes by reprising the nature and potential of 'BehSD' and by sketching how research adopting this perspective might go forward.

A note on terminology. SD uses 'behaviour over time' or BOT. This means the values of real world or model variables plotted against time. To distinguish them from 'behavioural effects', in this paper we refer to these as 'BOT trajectories' or just 'BOTs'.

2. Learning from the OR 'behavioural turn'

This section raises three 'methodological concerns' with the current state of BOR. This is done as a warning and to strengthen our subsequent application of behavioural ideas to SD.

2.1. Two definitional issues

A frustrating aspect of BOR is its looseness of definition. This manifests as both self-referential imprecision and potentially overreaching breadth.

The first is seen in attempts to define BOR. Specific references are avoided here but in the literature BOR is repeatedly 'defined' as an approach that includes 'behavioural aspects', a stance that considers 'human behaviour'. This self-referencing feels like writing 'X = X'; surely more is required of a definition. A sound definition is possible. Becker's (2016) is excellent. Though lengthy it is not self-referential, surely a better approach. However, this is unusual; an inward-looking lack of clarity is frequently seen in the literature. It is hard to get far unless this is avoided.

The second issue with current definitions of BOR is their breadth. In conference streams an astonishing variety of topics may be seen: reports on PSM-based interventions; laboratory experiments on decision-making under time pressure; reconceptualisations of the methodology of OR itself in term of 'behavioural aspects'.

It is healthy that interesting work on topics established for decades as part of OR continues to be presented. Yet suddenly these topics are 'BOR'? Does the label help, or is it merely a generous flag of convenience? As Lane (2017) observed, it was said of a certain class of sociological theory that they had little of substance but nevertheless had a;

> "… grim determination to blanket social reality with a vast conceptual quilt leaving nothing exposed …" (van den Berg, 1998, p. 222).

Is BOR merely an insubstantial but nevertheless extensive quilt? Convention has it that a broad church is a good thing. However, is BOR sustainable with such a very broad range of interest? A church with walls too wide apart risks collapse.

2.2. The question of novelty

It is a fallacy that BOR is a wholly original approach to OR methodology. Along with the urge of some of its enthusiastic converts to suggest otherwise, this perhaps explains the jaded reaction at OR56 – and offers a warning. The actual situation is well described by the UK OR Society's Behavioural OR Special Interest Group. The SIG's new website refers to:

> "…a long observed gap in 'people issues' in a wide sense… The recognition of this gap is not new, nor does it represent a revolution of the field of OR…"

An earlier version of that SIG's rubric was more colourful:

> "The field of O.R. has been aware of the relevance of behavioural issues, and might be said to have 'danced around them', ever since the 1980s."

(The core of this remark is also reproduced in the Preface to Kunc et al., 2016, p. ix). It is useful to place the behavioural turn in an historical context. For example, it is notable that Franco and Hämäläinen (2016b) called their editorial which introduced a special issue of EJOR 'Behavioural operational research: Returning to the roots of the OR profession' and speak of a "resurgence of interest in the study of behavioural issues" (both p. 791). They refer to work by Churchman (1970) and Ackoff (1977), and to Dutton and Walton (1964).

Questions concerning the roots of BOR – What are they? How far back do they go? - make for an enjoyable pastime. In purely chronological terms one can push the date earlier in the 1960s with Miser (1963) and Forrester (1961a), or leap into the 1950s with the work on socio-technical systems (Emery & Trist, 1969;

Trist & Bamforth, 1951). These all contain ideas similar to the interests of BOR.

Tracking the influences - works with elements now of interest to BOR researchers - is complex. In OR, the originators of PSMs deserve mention. The Introduction to Rosenhead (1989) draws out the common – arguably behavioural - themes of 'soft OR'. Also worthy of mention is the collection derived from an IFORS conference on using ideas from the social sciences to inform OR (Cropper, Jackson, & Keys, 1989). One paper offers 'A Behavioural Science Perspective on Operational Research Practice' (Burgoyne, 1989). Finally, Dyson, O'Brien, and Shah (2021) consider the originators of traditional, 'hard OR' and reveal ideas that relate to BOR discussions. Such thinking can become very expansive. The notion that our understanding of the world is not ruled by reason alone but involves numerous failings is central to Plato's Allegory of the Cave (a central conceit in Western philosophy) and can be read into the Hindu idea (expressed in the Bhagavad Gita) that humans are born into illusion.

Clearly BOR is not a new kid on the block. That is not necessarily bad: an old idea may have value because it has found its moment. The challenge is to clarify what specific new benefits BOR brings. Accepting that the general approach is not itself new, this paper aims to clarify the nature of the behavioural turn and explore what benefits it brings to SD.

3. The behavioural perspective - and its link to SD

This section offers a two-part clarification and a re-focussing of the core ideas of behavioural thinking. It goes on to consider the connection of those core ideas to SD.

3.1. Decision theory roots of the behavioural turn

Our understanding of the behavioural turn can be re-focussed by using a very specific decision theory example. The example reports an experiment (Tversky & Kahneman, 1974). School pupils were given five seconds to estimate the value of 8! but written as: $1 \times 2 \times 3 \times 4 \times 5 \times 6 \times 7 \times 8$. The correct (= logical, rational) answers is 40,320. The median of the pupil estimates was an under-estimate: 512. However, another group was asked to estimate the same thing - but written as: $8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1$. The median answer was still an under-estimate - but now 2250.

Tversky and Kahneman suggested that subjects were using an 'anchoring and adjustment heuristic' but with insufficient adjustment. Their explanation ran as follows. Since the subjects did not have time (or possibly the ability) to perform the actual calculation, they used a heuristic, a rule-of-thumb or short-cut. This heuristic consisted of getting a sense of how big the answer was from the first few terms in the expression and then adjusting that estimate – though not by enough - in light of the subsequent terms. Since '$1 \times 2 \times 3$…' looks smaller than '$8 \times 7 \times 6$…' this might explain the different medians.

This example has a tri-part structure that reveals much about the behavioural perspective. First, people err; they depart from a normative ideal, from rationality. Second, they do not do this randomly; it is empirically observable that they consistently depart in a certain way. Third, there is a (tentative) explanation for the phenomenon, based on the presentation of the situation and a theory (here cognitive and psychological).

It is worth observing that the behavioural perspective might look at the incorrect estimates of 8! and consider that these are not necessarily 'wrong'. Instead, in evolutionary terms, the view might be that the estimates derive from an approach which might be faster and therefore more effective for a different environment, an environment in which decision-making occurs in crisis situations where considered, full rationality is simply not appropriate. The lion strikes before the full analysis is completed whereas the 'rough idea' at least allows a rapid escape attempt. Heuristics are useful.

This example crystalises the behavioural approach. The structure is: puzzling departure from normative rationality; empirically observable alternative response; explanation that makes sense of the alternative in terms of human foibles, mental short-cuts, biases or failures.

3.2. Physics, foibles and failings: the broader effects

The behavioural view acknowledges that humans are not guided purely by rationality, not concentrating only on the 'physics' of a situation but are subject to failings, foibles and emotions. This is seen in specific situations (see 3.1) but it also operates in broader ways.

The Seventeenth Century orthodox model of the universe was the Ptolemaic System: the Sun, the Moon and the planets held fixed in vast crystal spheres, all rotating around the Earth. In 1610 the mathematician and astronomer Galileo Galilei took one of the telescopes that he had significantly improved and used it as a scientific instrument (Crump, 2001). Pointing it at Jupiter, he saw three bright 'stars' in a line. On seven nights he watched these stars, identified a fourth, and sketched their changing positions (Bixby & de Santillana, 1966). He concluded that these were moons, like the Earth's Moon, "four wandering stars revolving around Jupiter" (Galilei, 1610/2010, p. 29).

Galileo was an exponent of libertas philosophandi, "freedom from restriction by authorities and received doctrine, freedom to apply and interpret sense data" (Sutton, 1953, p. 313). To him it followed directly that the Earth was not the centre of all motion, that there were no crystal spheres. He had long suspected this but now Ptolemy's model was clearly refuted by empirical data. Galileo believed that the observations gave proof of his ideas and that any person could use a telescope to see for themselves, then rationally think for themselves and so change their fundamental view of the Universe. This is not what happened. Brecht gives a version of why. His 'Life of Galileo' has a scene around a telescope in which Galileo predicts how people will react. However, his friend is less sure:

> Galileo: Look, Sagredo, I believe in Humanity, which means to say I believe in human reason …
>
> Sagredo: Then let me tell you something. I don't. Forty years spent amongst human beings has again and again brought it home to me that they are not open to reason.
>
> (Brecht, 2006, p. 29)

Galileo's stance led to conflict with the Roman Catholic Church. In 1633 he was examined by the Inquisition, forced to recant and sentenced to indefinite house imprisonment having been found "vehemently suspect of heresy" (Crump, 2001, p. 55). Human behaviour, then, is not solely governed by reason. This general view is central to the behavioural turn.

Beyond this one historical example, the consequences of behavioural effects can be very broad indeed. A political economist argues that cognitive failings in the electorate result in feelings of nostalgia, fear and resentment becoming dominant political factors, leading to the rise of populists and nationalists (Davies, 2018). A political scientist sees 'cognitive problems' as part of the reason humans find it hard to implement policies that handle the short term costs vs. long-term benefits balance needed to address climate change (Caney, 2019). A philosopher suggests that cognitive limitations and our consequential failure to deal with climate change will result in Homo sapiens having to alter its self-image since, "we will increasingly experience ourselves as failing beings" (Metzinger, 2013/17, p. 2). A data scientist argues that behavioural effects may be central to human happiness (Chai, 2021). The behavioural turn can be applied to a very wide range of phenomena.

3.3. The connection with System Dynamics

In this section a key application of the behavioural turn to SD is described. It employs the three-part structure of the example in 3.1. However, both this structure and the general spirit evoked in 3.2 also underlie the ideas presented in the later sections.

A work critical in generating interest in BOR is the paper by Hämäläinen, Luoma, and Saarinen (2013). Yet it concerns stock and flow thinking from SD. The stock and flow distinction is central to SD (Forrester, 1956, 1958b; 1961a, 1961b). Stocks are state variables, the integrals in the system which accumulate the net rate of (in)flow. Computer simulation is vital to generate the trajectories of such complex systems over time (Forrester, 1970/1975). However, for the last two decades system dynamicists have been exploring how individuals perform 'mental integration'. Subjects are given information about the rates flowing into and out of a stock and then asked questions about the stock. For example, Booth-Sweeney and Sterman (2000) explored a 'bathtub task': subjects were shown a square-toothed graph representing water flowing into a tub, and a constant outflow, and asked to sketch the amount of water in the tub. Subjects were poor at this: few produced the correct 'saw-tooth' pattern (the integral of the linear, square-tooth function). SD is replete with such experiments (Booth-Sweeney & Sterman, 2000; 2007; Strohhecker & Leyer, 2019). Water is sometimes re-cast as cash flows and the stock as cash reserves (Booth-Sweeney & Sterman, 2000), or as carbon emission and absorption rates and the resulting atmospheric content (Sterman & Booth Sweeney, 2007), or other combinations (Kapmeier, Happach, & Tilebein, 2017).

Ideas vary for why humans are so poor at these tasks: not all people study calculus; people with calculus do not think to apply it to such homely situations; people assume a form of direct, correlational relationship; people assume the pattern for the stock simply must be the same pattern as that of the flows (Cronin, Gonzalez, & Sterman, 2009), people think in too narrow a way (Fischer & Gonzalez, 2016) etc. The over-arching reaction to these results is that simulation modelling is needed and SD can save the day.

Hämäläinen et al. (2013) made their case for BOR with an example of the mental integration problem. In the 'Department Store Task' (Sterman, 2002, after Ossimitz, 2002) participants are shown a graph of the number of people per minute entering and exiting a store. They are then asked four questions. These seek numerical answers but offer a 'Can't be determined' option. Two questions are about the flow rates: 94% of the subjects answered correctly. Two more are about the number of people in the store: only 42% and 30% answered these 'integral' questions correctly, whilst another 17% and 28% respectively chose 'Can't be determined'.

In stark contrast to previous SD work, Hämäläinen et al. suggested that behavioural issues were involved: the experience of being able to answer the flow questions by direct reference to the graphs encourages subjects to try the same approach with the stock questions (but this proves impossible); the way that the maxima and minima of the flow curves stand out triggers what Tversky and Kahneman (1974) called the 'availability heuristic'; the presence of the option boxes suggests (incorrectly) that some questions are too hard to answer; people are cognitively overwhelmed by the need to compare areas under the graph.

Attempting to remove these issues, they re-worked the experiments in 11 variations: rephrasing the questions, encouraging people to think more deeply about their responses, in some cases smoothing the graphs. The authors observed statistically significant improvements in the two stock-related questions, correct responses rising to 55–90% and 48–76%.

Their first conclusion was that the existing flat assertion 'people can't deal with accumulation' would not stand. Instead, they suggested that the presentation and the cues imbedded in accumulation-related questions can significantly influence people's ability to deal with accumulation. Their second conclusion, the most important assertion of this paper, was that behavioural effects apply broadly across OR and merit further research.

There is other similar experimental work. One example leaves the task unchanged but 'primes' participants to use analytical thinking (Baghaei Lakeh & Ghaffarzadegan, 2015; 2016), and there has been other work on the presentational aspects (Howie, Sy, Ford, & Vicente, 2000). In both cases results are consistent with a behavioural interpretation. However, Hämäläinen et al. used an example from SD but sought to apply behavioural thinking across OR. Their paper is discussed here because its argument has the same structure as that considered in 3.1: departure from normative rationality (people incorrectly calculate values of stocks); alternative response observable in experiments (questions about flows are answered better than those about stocks); explanations that makes sense of the alternative in terms of human foibles, biases or failures (people find mental integration challenging but this is influenced by how data is presented, what cues the questions give them and whether they are encouraged to reflect deeply on the question). This structure is well established in the 'mental integration' work in SD. Hämäläinen et al. were not the first to suggest ways of assisting the thinking of those tackling such tasks (Gonzalez & Wong, 2012; Pala & Vennix, 2005; Qudrat-Ullah & Kayal, 2018; Stouten & Groessler, 2017). Nevertheless, the example is a sound platform for their case for BOR: the specific argument having been made, the authors offer a broad interpretation of what BOR should be:

> "behavioural effects can relate to the group interaction and communication when facilitating with OR models as well as to the possibility of procedural mistakes and cognitive biases." (Hämäläinen et al., 2013, 623)

This paper responds to that significant insight by applying the behavioural turn to SD and across many more aspects of the SD field. On the basis of the clarification and re-focussing of behavioural ideas above, the case is as follows. Section 4 provides examples of the nature and breadth of that applicability whilst Section 5 examines the stages of an SD-based intervention, attempting a comprehensive and fine-grained account of how the behavioural turn applies.

4. Behavioural ideas at the core of SD

Franco and Hämäläinen (2016b) acknowledge the presence of behavioural ideas in SD. Certainly, from its inception the field contained a number of ideas with a behavioural feel: the insight that decision makers are not Homo economicus; the notion that playing with a computer model in a group can produce learning; the over-arching assertion that people are poor at dealing with complex systems. All this can be found in 'Industrial Dynamics' (Forrester, 1961a). These and other distinguishing features of SD are identified - even in 1984 - in the insightful review of SD from an OR perspective by Sharp and Price (1984). Similarly Towill (1994), adopting a manufacturing systems perspective, is clearly aware of issues relating to model ownership and validation, and the use of models to influence people, all things that we might now consider 'behavioural' in nature. A not dissimilar point has also been made, albeit briefly (Hämäläinen et al., 2013) but our view is that the case put there goes neither far enough nor wide enough. Recall our research question; 'Can behavioural concepts be applied to System Dynamics modelling in a useful way?' We argue in the positive, that the concepts apply to a range of issues that are the very foundations of SD modelling. In this section this is illustrated in two ways.

4.1. SD examples of 'naïve' vs. 'sophisticated' thinking

A way of illustrating this is to examine the insights that decades of SD work give into how people think when making decisions concerning complex dynamic systems. A tenet of SD is that normal human intuition is naïve when it comes to such situations but that modelling has the potential to produce a more sophisticated understanding of how a system is working and what needs to be done to steer it in a desired direction (Forrester, 1970/1975). To consider this we use a straightforward SD conceptualisation of 'mental model':

> "A mental model of a dynamic system is a relatively enduring and accessible, but limited, internal conceptual representation of an external system (historical, existing or projected) whose structure is analogous to the perceived structure of that system" (Doyle & Ford, 1999, p. 414)

To take a broad view of behavioural concerns found in the literature, we use the dichotomy 'naïve' and 'sophisticated' thinking. The wide-ranging research basis of this dichotomy is explored in more detail below and also in Section 5.

For our purposes here, broadly put, 'naïve thinking' is unconsidered and superficial, perhaps the result of time pressure or an inadequate mental model, and involves the use of simple, possibly fallacious ideas, and short-cut thinking and heuristics. It also serves to describe what is mostly seen in reality. In contrast, 'sophisticated thinking' involves more reflection, frequently with more developed mental models, normatively correct diagnoses derived from deep, reflective and rationally correct evaluation of a complex situation. It is the type of improved intuition that SD aims to engender in policy makers.

This dichotomy can be applied to show how a behavioural perspective can illuminate some of the most well-known phenomena studied in the SD field (Table 1). Note that this is an appreciably expanded and re-organised form of a more narrow analysis in Lane (2017). As indicated by the citations below, these phenomena have been observed multiple times in experiments and documented in case studies. Applying the dichotomy proves revealing.

The field was created as a result of Forrester's attempt to understand oscillations in the inventories of an electronics manufacturer, his insights leading to the discovery of the 'bullwhip effect' (Forrester, 1958a; Lane, 2007). The modelling work led to a board game – 'The Beer Game' - which has now been played many times over half a century, reproducing the supply chain oscillations (Jarmain, 1963; Lane, 1995; Larsen, Morecroft, & Thomsen, 1999). Analysis of game behaviour reveals a range of behavioural insights. Amongst those, it was found that players gave insufficient attention to the supply line of past orders when deciding how much to re-order and so over-order (Gonçalves, 2018; Oliva & Gonçalves, 2005; Sterman, 1989). The naïve approach tacitly accepts that keeping an accurate account of past orders is hard when there is time pressure and therefore does not make this a priority. A sophisticated approach would involve making the effort to account fully for what has already been ordered (Gonçalves & Moshtari, 2021). The fact that naïve thinking is used is an important part of explaining the empirically observed oscillations.

The nature of this example is similar in style to that of 3.1: time pressure causes short-cuts in decision-making when full analysis seems impossible. Its location at the founding of SD shows how deeply embedded in the field behavioural concepts are. The further examples of Table 1 are covered more briefly since the pattern is clear and the table provides detail.

Note that the phenomena are organised here into a hierarchy that moves from one element of a particular decision rule, through an appreciation of feedback loops, finally reaching the role that SD models aspire to play in policy analysis.

Example 2 operates at the level of a 'generic structure', a combination of feedback loops observed in many different domains (Lane & Smart, 1996; Paich, 1985; Rahn, 1983). Humans who

Table 1
Applying the behavioural turn to SD – various phenomena of interest in SD, explicated using 'naïve' versus 'sophisticated' thinking comparison.

Phenomena of interest in SD field	Ways of thinking about what to do	
	Naïve	Sophisticated
1. Not remembering past actions makes supply chains oscillate ('Beer Game')	• When making time-pressured re-order decisions, keeping track of past orders is just too hard - but anyway is not a priority.	• It makes sense to take full account of past orders in the supply line when making re-order decisions.
2. Humans keep using a policy that has ceased to work ('Limits To Growth')	• The helpful compounding effect is the only mechanism in play. • This effect worked in the past so we should try to make it keep working.	• There is a compounding effect but its previous success has hit a limit • Broader thinking addresses this limit to reinvigorate growth.
3. Humans fail adequately to anticipate consequences of policies	• Causal chains are short, simple and direct. • Relationships are linear and instantaneous. • Effects have a single cause, effects are proportional to causes.	• Causal chains may be long and may involve feedback. • Relationships may be non-linear and involve accumulation or delay. • Effects are multi-determined and may relate to causes non-linearly.
4. Humans find it hard to intuit behaviour of complex dynamic systems	• My mental model is complete and correct. • My mental model is appropriate for use as an enduring basis for action. • When making decisions, I can infer in my head the consequences over time of my mental model.	• My mental model may be wrong or incomplete. • I should keep questioning, testing and improving my mental model. • I need support if I am rigorously to deduce the consequences of my mental model.
5. Humans resist the use of modelling for policy analysis	• A model is too slow to build and cannot express all that is known about an organisation. • Forecasting the future is simply not possible; we cannot predict what will happen. • If a model behaves strangely then it is wrong and therefore useless. • Gut-feel is a sound guide to action; leaders lead.	• Policy decisions merit reflection; a model can allow deeper consideration of more aspects. • Scenario analysis is useful; we can be prepared for the range of things that might happen. • Surprising behaviour is a chance to learn, to improve intuition. • Formal modelling allows ideas to be shared and understood and can create commitment to action.

experienced rapid growth produced by a reinforcing loop are observed to continue trying to push on what they perceive to be its underlying causes, chained to a policy which is no longer effective because a resource limit has now come to dominate the system. Deeper thinking might move attention to addressing that 'limit to growth' (Meadows, Meadows, Randers, & Behrens, 1972).

The third example applies across social systems generally. Anticipating the consequences of policies is difficult. This is because humans are observed to act in a manner consistent with the idea that causal chains are short and feedback loops rare, effects are proportional to causes and occur rapidly (Axelrod, 1976; Dörner, 1996; Dörner, Nixon, & Rosen, 1990; Plous, 1993). In contrast, SD takes the view that effective policies can only be crafted after careful consideration of the complexity of social systems (Forrester, 1960; 1961a; 1987b; Meadows, 1982).

Directly following is the SD case for mental model elicitation and computer simulation, example 4. Social systems frequently exhibit counter-intuitive behaviour. This is a result of two errors. First, as described in example 3, the mental models (of both individuals and groups) may be deficient and/or too simple. In fact, only "accurate mental models lead to better decision rules and higher performance" (Gary & Wood, 2011, p. 1097). Second, the erroneous belief that mental models can be rigorously 'interrogated' purely by cognitive means. In fact, the human mind is incapable of working through the consequences of a complex mental model; inference, or 'mental simulation' is inadequate (Lane & Oliva, 1998). In response, SD employs (respectively) group processes for knowledge elicitation and representation to improve understanding of systems (Vennix, 1996), and computer simulation rigorously to deduce the response of a complex system (Forrester, 1973; 1987a, 1992b).

Example 5 concerns the difficulties encountered when trying to persuade policy-makers of the benefits of simulation modelling. Managers are busy and doubtful of the ability of a model to represent their organisation or to do anything useful (Forrester, 1971; Mintzberg, 1990; Sterman, 1988), even though both rational thinking and a rational process are an accepted - albeit hard to obtain – ideal (Cabantous & Gond, 2011). A naïve approach makes it easy to view modelling as unnecessary, a fruitless waste. However, a sophisticated approach is more open to the benefits of computer simulation, a tool which though requiring investment of effort, yields rigorous holistic thinking and can act as a learning, persuasion and communication device (de Geus, 1988; Lane, 1992; Rouwette, Korzilius, Vennix, & Jacobs, 2011).

We would argue that, to date, the explicit interest in behavioural effects in the SD field has tended to focus on the structure of particular decision rules and policies, on including behavioural features within models. A stronger response to our research question is obtained by taking a broader view. This is indicated in the above examples, moving as they do from the structure of a particular policy (1), through perceptions of a system structure (2), to more general points about how people think about (3) and understand (4) social systems and their reaction to using computer simulation (5).

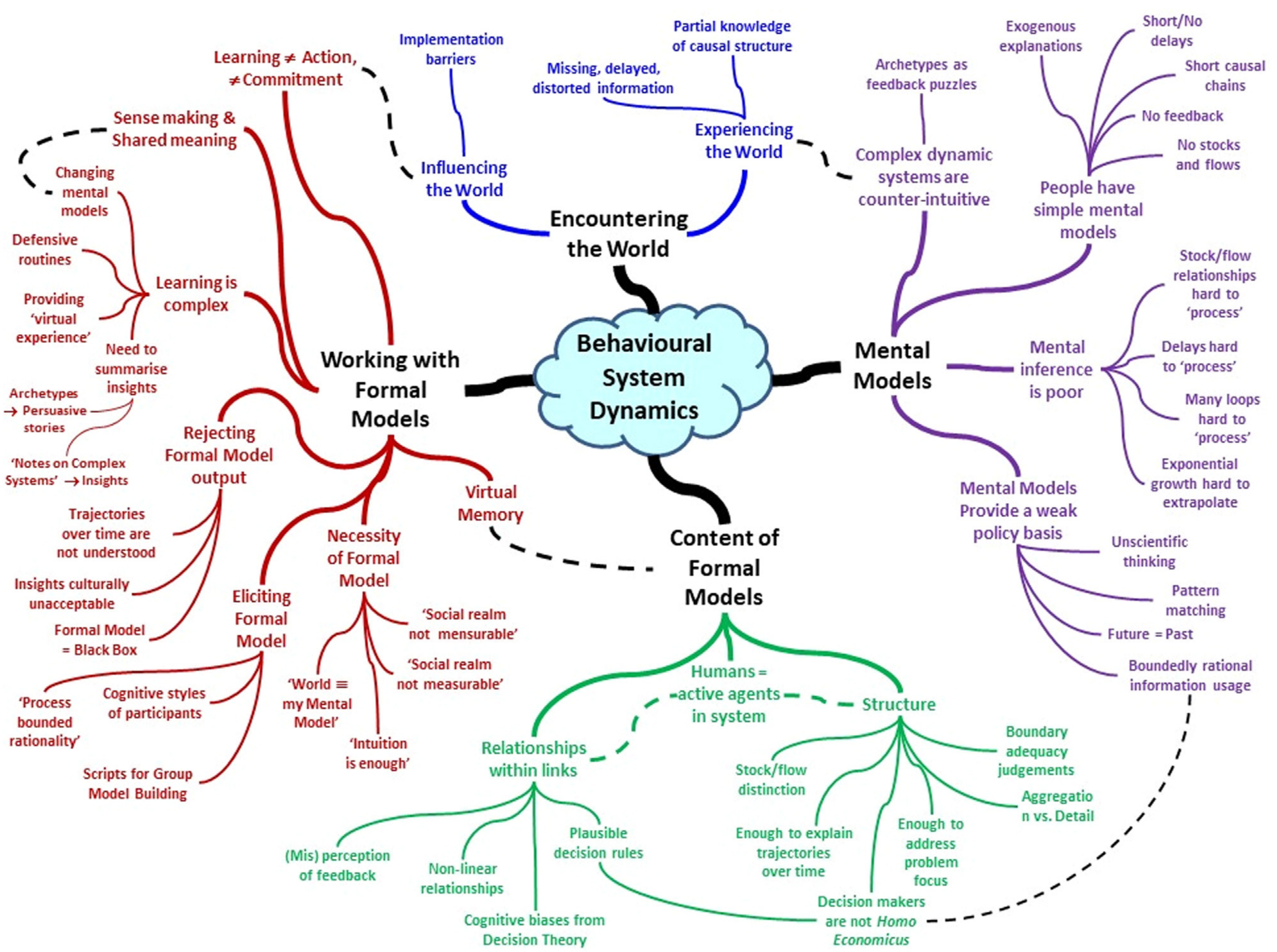

Fig. 1. A mind map of issues and phenomena arising in SD that relate to the behavioural perspective. Note that mentioned here are 'archetypes' from the work of Meadows (1982) and Senge (1990), and the summarising 'Notes on Complex Systems ' from Forrester (1969). This map can be read clockwise and the areas loosely relate to those in Fig. 3.

4.2. Elements of an SD study

This paper argues for a ‘Behavioural SD’ which opens out the behavioural turn as it applies to the field, and applies it both within and around models. One means of doing that is the ‘tentative map of the behavioural SD territory’ proposed by Lane (2017). This used a ‘mind mapping’ approach: a range of specific effects considered in the SD literature are positioned using four different elements of an SD-based modelling study. An amended, extended and completely re-organised version of that first attempt is shown in Fig. 1.

The map still only hints at the process of modelling: there is a notion that one starts at the 12 o’clock position and then moves clockwise around the map, from encountering the world via experience, round to mental model-related issues, on to formal models (first with their content and then with the process of working with them) and finally re-encountering the world by trying to influence it.

This map as somewhat useful in indicating that behavioural ideas indeed lie at the core of SD. But it is insufficient. More clarity about the modelling process is required. The following section therefore presents a new approach which is more rigorous and which aims to strengthen our response to this paper’s research question.

5. Behavioural effects in the context of the SD modelling process

5.1. A framework for the scope of ‘Behavioural SD’

Here we offer a new framework for behavioural issues as they apply to SD. Motivated by the limitations of the mind mapping approach, it gives a more clear representation of the stages of SD modelling and the processes that are undertaken whilst also aiming to be more extensive (though not comprehensive) in its ability to locate the relevant behavioural issues.

The framework draws on a range of discussions and/or representations of the elements and assumptions of SD modelling in the literature of theory and practice. These include: Mass (1986), Morecroft (1984), Randers (1980), Richardson and Pugh (1981), Richmond (1987, Roberts, Andersen, Deal, Garet, and Shaffer (1983), Sharp and Price (1984), Vennix (1996)), Ford (1999), Maani and Cavana (2007), Morecroft (2007) and Meadows (2008), Zagonel (2002), and particularly Sterman (1994) (which itself draws on some of those sources). We also include the group effects considered by Forrester (1971), Vennix (1996, 1999), Andersen, Vennix, Richardson, and Rouwette (2007) and Rouwette and Smeets (2016).

In what follows we use boxes and arrows. Some previous work uses these as mere visual organisers, their meaning left at best implicit, sometimes inconsistent, at worst obscure (c.f. Lane & Husemann, 2009). In contrast, we have tried explicitly to clarify the meaning of the symbols. The boxes and arrows are activities and processes, sometimes involving an individual, sometimes a group. However, there is a distinction. The boxes indicate entities or representations, more enduring platforms in which information and opinions are configured or arranged. The arrows indicate actions or influences, channels which result in one entity or representation having an effect on another. In the following we define each element. The framework is presented in three stages, first in the absence of a formal model, followed by a treatment of group effects, then with the use of an SD model.

5.2. In the absence of formal SD modelling: individual effects

Fig. 2 depicts a process of decision making unaided by any supporting tools. We start with the ‘real world’, the existing state of things. Note that, “It will be enough, for our purposes, to define “reality" as a quality appertaining to phenomena that we recognize as having a being independent of our own volition (we cannot “wish them away")” (Berger & Luckmann, 1966, p. 1). More bluntly, "Reality is that which, when you stop believing in it, doesn’t go away" (Dick, 1995, p. 261). ‘Experiencing the world’ follows - but the real world is only partially knowable. Not all information is perceived because our sensory apparatus registers only some forms of information and not others. For example, we generally

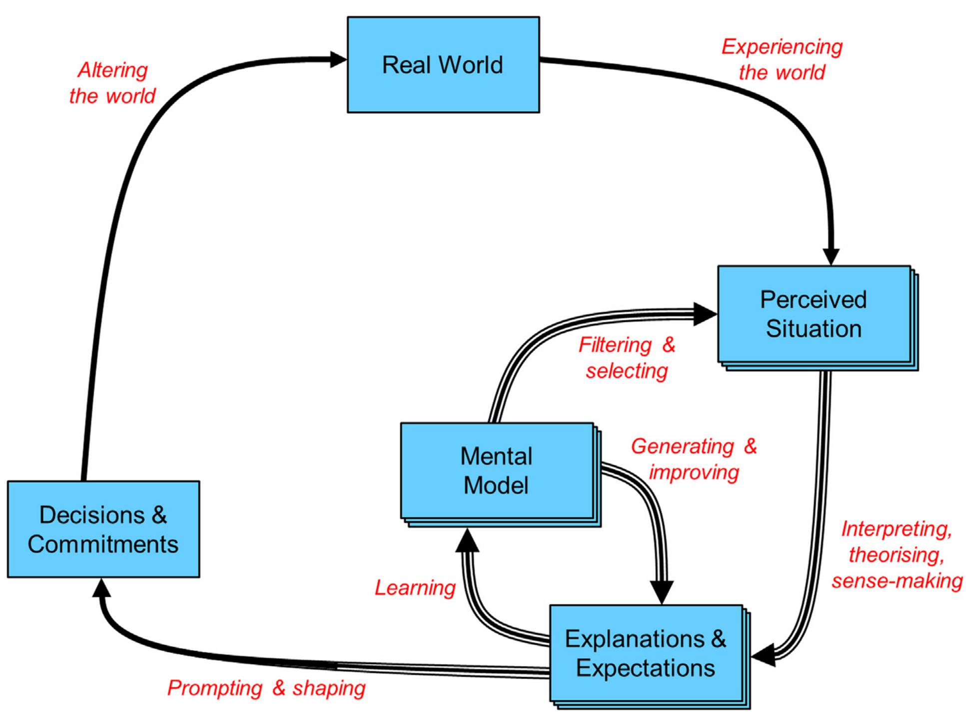

Fig. 2. Framework illustrating the location and role of behavioural effects relevant to SD when no formal model is involved.

register sounds with frequencies between 20 Hz and 20 kHz, because of the way the human ear and central nervous system operate (Gelfand, 1988). The 'perceived situation' thus refers to one's awareness of a state of affairs - built up, in part, on the basis of our senses. However, that awareness does not purely result from physiology. Of the information that is in-principle available, some will be attended to whilst other elements will be ignored. The selection of what to pay attention to is in some cases automatic, for instance when a loud sound immediately draws attention (Kahneman & Henik, 2017). However, in many cases directing attention is a more subtle process, and driven by our memory of similar situations that were encountered before. For example, when trying to learn a new skill, such as using a new software package: the situation appears confusing at first because it is not clear what to pay attention to, which actions are possible and what the results will be; it is only after some trial and error that actions and results become clearer and begin to make sense (Schank & Abelson, 1977).

This and other effects on the perceived situation are a result of our 'mental models'. Formal definitions of this term are varied across different disciplines and not always clear (Doyle & Ford, 1998). At this point we mean here the SD-related understanding of the term (see Section 4.1 and for more recent elaboration Groesser & Schaffernicht, 2012). This internal conceptual representation includes ideas in use about the relevant variables, their connecting causal mechanisms and the time horizon of interest. Such representational mental models are built and refined over time and they are involved in the 'filtering and selecting' of the information considered important in perceiving a given situation. The concept of mental model is considered further below.

Perceptions of the real world are interpreted and regularities inferred, leading to (implicit or explicit) theories that make sense of what is observed ('interpreting, theorising, sense-making'). This leads to 'explanations and expectations': a decision maker's understanding of what is happening around them and their mental predictions on future states of affairs.

Mental models are involved here too, since they are 'generating and improving' situation-specific explanations and expectations. An enlarged definition explains this. Richardson, Andersen, Maxwell, and Stewart (1994) distinguish three elements of mental models: an ends model (involving a norm about desirable states), a means model (which involves options for action) and a representation of the dynamic system. These work as follows. A decision maker considers their perception of the current situation and expectations about the future situation. Using the ends part of the mental model, this is compared with what is desired. If the gap between perceived or expected situation and desired situation is too great, then the means model guides expectations regarding alternative actions that may close the gap. The representation part of the mental model offers a 'means-ends check': testing and improving thinking about what consequences an action can be expected to produce.

However, in causal terms, explanations are severely limited because people have simple mental models (Axelrod, 1976; Dörner et al., 1990; Schaffernicht, 2018). Unbalanced paths - when factor A has a positive effect on factor B via one path, and a negative effect via a second path - are misunderstood; people tend to simplify this causal network, focussing only on one of the two paths. Closed causal chains - feedback loops in which actions lead to consequences that in turn feed back to the initial point of action - are often not recognised at all. Delays are thought to be short and a distinction may not be made between what modellers would call stock and flow variables.

Expectations are also problematic. Even when full information on structure is provided and/or the system concerned is very simple, people have difficulties inferring the dynamic consequences of a mental model (Lane & Oliva, 1998). Mental models therefore provide a weak basis for thinking about policy. In the bath tub task described in Section 3.3, the constituent elements are understood and the consequences over time tractable in principle. But most people are unable to deduce the trajectory of the stock. The same is true of the department store task. Instead of deducing the trajectory by incrementing the value of the stock with the difference between inflow and outflow (= the net flow), most people base their answers on heuristics such as pattern matching: guessing that when the net flow is largest, the stock must be at its maximum value too (Cronin et al., 2009). The presence of many feedback loops, non-linear relationships and long delays also produce difficulties and this has been explored experimentally (Özgün & Barlas, 2015).

When new or unexpected situations are encountered, the existing mental model is first used as described above, as a basis for generating and improving explanations and expectations. However, if the existing mental model does not offer an adequate explanation for what is experienced, new explanations and expectations are formed and an updating cycle will start: 'learning' leads to an altered mental model, which guides and improves future explanations.

Because situation-specific explanations and expectations may involve comparisons of perceived versus desirable states (and candidate actions for closing the gap between the two), they are central to the 'prompting and shaping' of such actions. The creation of 'decisions and commitments' typically involves choosing amongst a range of possible actions involving allocating resources or agreeing to a certain undertaking. But again, behavioural issues arise. When making a choice, humans do not perform an exhaustive scan of all possible actions and their consequences, or in others words, do not make rationally optimal choices (March & Simon, 1958). Instead they choose actions that satisfy minimal criteria and therefore can best be described as boundedly rational. Additionally, such actions may be chosen not in a spirit of trying better to understand the real world but rather to obtain a particular response, such as financial return, and there may be issues concerning how consistently actions are actually implemented, whether they are implemented at all (Sterman, 1994).

The final step in Fig. 2 is to implement the chosen actions thereby 'altering the world'. Seeing if an action leads to the desired changes in the real world helps to test explanations and expectations and thereby enrich mental models. The cycle continues.

However, that cycle has numerous shortcomings; there are even more behavioural effects than already described. There is a large literature on the limitations of human rationality for each of the stages described in Fig. 2. A key work on forecasting and planning points up a set of flaws in the way that many of the steps are conducted (Hogarth & Makridakis, 1981). Regarding our perceptions of a situation, when prioritising what to look at in the real world, people tend to seek out information that is consistent with their own views rather than 'scientifically' look for information that can refute their expectations (Plous, 1993). Such 'confirmation bias' was observed by Jane Austen: "How quick come the reasons for approving what we like!" (Austen, 1818/2003, p.16). Also concerning perception, there is a non-linear relationship between distinctions in external stimulus and our perceptions of them; the Weber-Fechner law applies (Fechner, 1860). So two light bulbs are not seen as emitting double the light of one, and small children locate 'three' mid-way on a line with ends marked with zero and ten (Sun, Wang, Goyal, & Varshney, 2012; Varshney & Sun, 2013). When forming explanations and expectations, people have difficulties in extrapolating growth processes (Wagenaar & Timmers, 1979) and, hence, in making rapid decisions to deal with such processes (HoC H&SC and S&T Committees, 2021). Decisions and commitments are by no means rational: in a series of investment decisions, people who received negative feedback on previous decisions invested more than those who received positive information, an example of irrational 'escalation of commitment' (Staw & Ross, 1987). Looking for confirming information and continuing with a failing course of action are both examples of how individual judgements influence the interpretation of data. Biased interpretation of data, paired with the incomplete causal understanding and inability to infer dynamic consequences discussed earlier, makes humans poor at learning, at improving their mental models. The list of such effects is very long – and the effects well documented.

5.3. In the absence of formal SD modelling: group effects

The description so far dealt only with issues concerning individual decision making. This is not the whole story. Often, as is the case for juries, teams and corporate boards, responsibility for important decisions is assigned to groups. This is indicated in Fig. 2: some of the activities and processes are multi-layered (the boxes) or multi-stranded (the arrows). Some of those arrows are entirely multi-stranded, indicating an activity that continues to involve a range of effects, participants and voices. One shows multi-strands merging into a single strand, indicating that agreement or accommodation takes place. This involvement of groups of people requires the consideration of a new set of issues.

Studies of group decisions reveal shortcomings in each of the stages discussed in 5.2. One would expect that groups have more information available than an individual, and are better able to check on procedures followed to translate information into decisions. However, Kerr, MacCoun, and Kramer (1996) show that groups are not always less biased than individuals. Which of the two is more biased depends on such factors as group size, type of bias (e.g. using too much or too little information) and nature of the group process. Similar to an individual, when a group considers what to do about a particular issue, a first step is to select which elements of the real world to concentrate on. In this selection process, the division of information over group members plays an important role. If information is shared amongst many group members, it is likely to be mentioned and considered in making a decision (Stasser et al., 1989). In contrast, if it is known by only one person it may not be brought forward or, when it is, it may be treated as mere opinion. While in both individual and group decision making the demands of a task play an important role, for groups there is a greater need to balance task demands with socio-emotional demands. For instance, in the extreme case of 'group think' (Janis, 1982), groups which find themselves in a challenging context, and which are at the same time very cohesive, may pressure individual members to follow the group norm. The UK response to the SARS-CoV-2 pandemic is a public policy example (HoC H&SC and S&T Committees, 2021). The dual demands on groups that are making decisions - concerning both information processing and management of social relationships - have recently been receiving more attention in the literature (de Dreu, Nijstad, & van Knippenberg, 2008).

5.4. Introducing a formal SD model

The new elements in Fig. 3 show how SD can support decision making. Whilst mental models are implicit, SD models represent explicitly the structure thought to underlie, or best make sense of, a dynamic problem.

There may be resistance to the idea of doing formal modelling, for example, based on the notion that managerial intuition is sufficient, or that everything about the world is already known and taken into account. Potential users may also feel that there are aspects of their world that are conceptually incapable of being measured, or certainly not able to be measured with any accuracy (see Coyle, 2000; Homer & Oliva, 2001).

Having started to develop an SD model of a problem of interest, relevant concepts, relations and loops need to be elicited, expressed in verbal form and then represented using conceptual or simulation models. For a group this will involve a process of negotiation, persuasion and agreement. The resulting 'formal SD model' may be qualitative but usually describes a problem state in quantitative parameters, and the mechanisms thought to govern transitions between states in the form of equations.

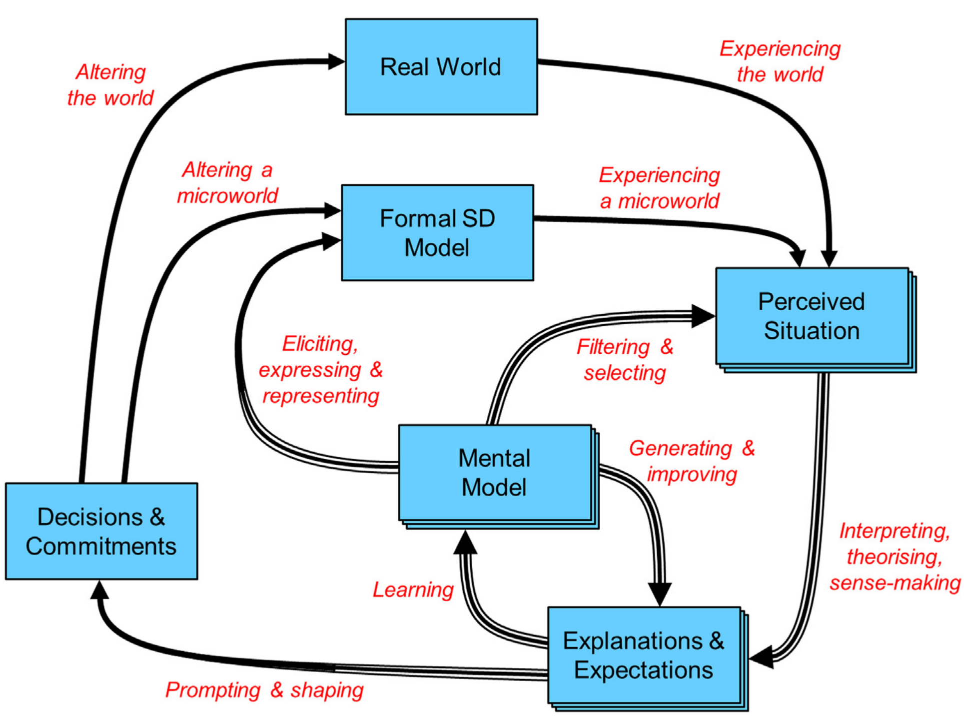

Fig. 3. Framework illustrating the location and role of behavioural effects relevant to SD when a formal model is created and used.

Table 2
Examples of behavioural effects in decision making (first column) and how these are addressed (for individuals and groups) by using SD models. However, note that this introduces new behavioural effects.

Shortcomings of unsupported decision making	Contributions to decision making support from the use of system dynamics	
	Individual	Group
Not all relevant information used	• Avoid a focus on preference-consistent information by building model structure that generates problem symptoms.	• Avoid negative impact of socio-emotional demands on task, by a facilitator-guided process.
Incomplete testing of explanations and expectations	• Explicit testing of hypotheses regarding the effect of parameter changes.	• Facilitated process of eliciting, confronting, agreeing on and representing relations between variables.
Incomplete integration of novel explanations and expectations in mental model	• Iterative construction of transparent causal model. • Exploring dynamic consequences of model structure. • Tracing causes of surprising model BOT trajectories. • Condensing structure-trajectory insights using storytelling and archetypes.	• Using group input to construct transparent causal model, checking consensus on proposed model changes. • Group-based formulation of expected dynamic consequences of model changes, testing of expectations.
Limited consideration of explanations and expectations in shaping decisions and commitments	• Avoid only looking for solutions close in time and space to problem symptom, by using explicit model structure.	• Silo-based decision making/departmental bias counteracted by considering wider range of decision options, based on explicit model structure.

The process of transforming mental models into an SD model ranges from analyst-driven (using mainly academic publications and policy documents as input), via information elicitation using interviews, to a fully participatory mode in which decision makers, experts and stakeholders build model structure and explore dynamic implications together (Antunes, Stave, Videira, & Santos, 2015; Cockerill, Daniel, Malczynski, & Tidwell, 2009; Franco & Montibeller, 2010; Lane, 1992; Richmond, 1987; Vennix, 1996). Decisions and commitments are translated into model alterations: changes in parameters and structure. When a formal SD model has been built, experimenting with reality can be supplemented by first testing decisions by simulating the model. This is risk-free, with no fear of consequences in the real world - indeed, that is one aim of using the model. It is a ‘microworld’ (Morecroft, 1988) which allows ‘vicarious experience’ (Eden & Sims, 1981); it serves as a ‘managerial practice field’ (Senge, 1990), a device for ‘playing’ with ideas and learning (Papert, 1980). Users have perceptions of model output (the new ‘perceived situation’), debate new explanations and expectations and use this ‘modelling as learning’ (Lane, 1992) to update their mental models. The new mental models will be an input to experiencing the perceived situation (Rouwette, Größler, & Vennix, 2004).

In SD, model-based support, both in the form of model construction and policy testing, improves decision making in a number of ways as shown by the examples in Table 2. This Table is based on Sterman (1994) and Vennix (1996) but is also grounded in the various works of Forrester cited throughout this paper. The point to note is the behavioural effects that are encountered, the way that SD attempts to address them and how those attempts introduce new behavioural effects.

6. The nature and benefits of ‘BehSD’

This section aims to show how researchers might apply the behavioural turn to SD, what that might look like and what benefits follow. It shows how the framework of Section 5 contributes, and then offers some foundation stones necessary to move towards a fully developed theory of ‘Behavioural System Dynamics’ (BehSD).

6.1. Behavioural effects in context

Returning to our research hypothesis, we add to the ideas in Fig. 1 and Tables 1 and 2 and put the framework to use, illustrating its potential for exploring behavioural effects in SD and improving practice. There is no attempt to illustrate all of this information in one over-burdened figure. Instead, Fig. 3 is the framework whose more coherent account of the process of SD can be opened up piece by piece to display specific behavioural effects known to be relevant there. Moreover, it acts as a context, an instrument, for exploring those effects and increasing our understanding of them, and for uncovering links to new effects. By showing how behavioural ideas apply to SD, the material here also returns to this paper’s research question. Three examples of this approach are given below.

6.1.1. Behavioural models provide plausible explanations

This example considers in more detail some of the boxes within the framework and the need to represent behavioural effects within a model.

An SD study starts with a ‘BOT trajectory’. The aim would be to try to explain the unwelcome BOT by detecting the policies underlying it – and then using this explanation as the basis for crafting better policies (Forrester, 1961a, 1968a). However, this is only possible with a realistic representation of decision making. As introduced in 5.2, and included in Fig. 1 (bottom right), decision makers are not the fictional Homo economicus who deeply ponders and, “who maximises utility using maximal information, and is uninfluenced by others” (Government Office for Science, 2018, p. 10). Economists today adopt the behavioural view that people use only a small amount of the information available to them; they are “perhaps Homo imperfectus" (Government Office for Science, 2018), trying to find a satisfactory outcome.

Starting with this mental model of decision making, a series of behavioural phenomena is unearthed (see Fig. 4). Humans are considered to exhibit bounded rationality, seeking only to ‘satisfise’ and having to work quickly (Ackoff, 1977, see also Gigerenzer & Goldstein, 1996 and Kahneman, 2003; March & Simon, 1958; Simon, 1955; 1957). Those ideas can be represented within a formal SD model. The canonical example is the work of Morecroft (1983, 1985). Such a model allows users to simulate and hence perceive the BOT trajectory that results from those mental model assumptions, as well as the underlying causal structures and policies that express them. The explanation is itself a profoundly behavioural one: the SD maxim that structure influences BOT holds. However, this has required including within a model key behavioural assumptions about human decision making. On that basis, improved policies can now be crafted – for further examples, see Lyneis (1980).

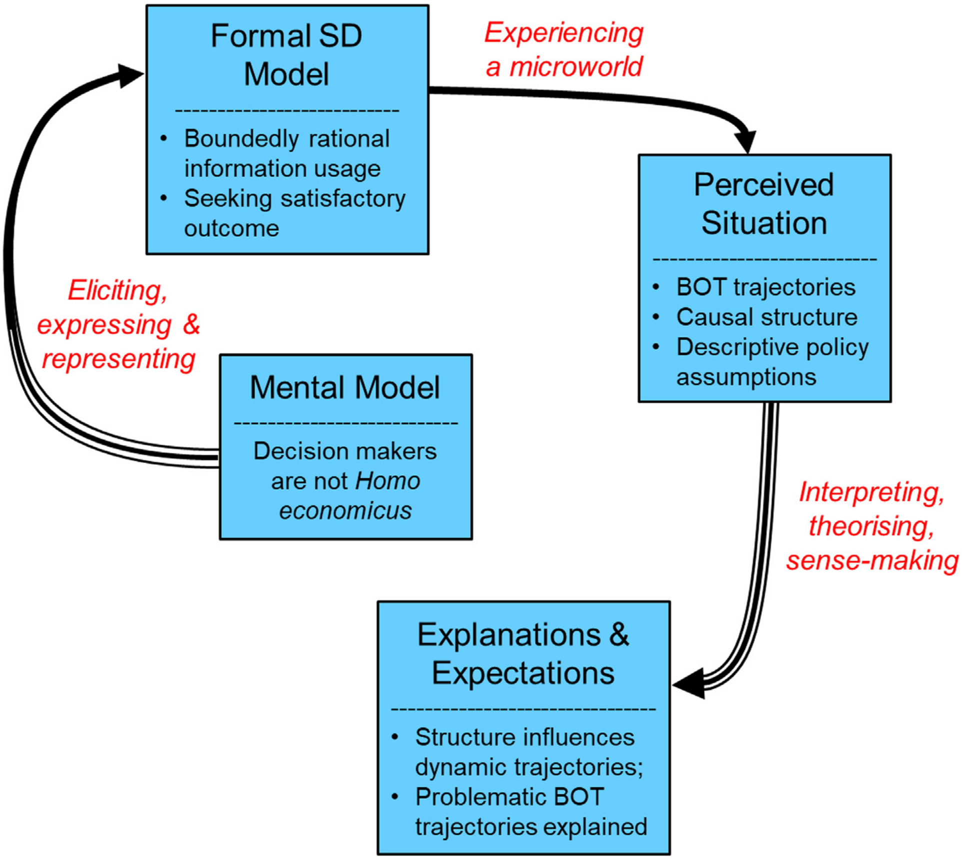

Fig. 4. Use of the framework to illustrate the benefit of building into SD models behavioural assumptions relating to actual decision making.

The framework both locates the key mental model assumptions and helps make sense of their contribution to SD. Practice is improved because including the behavioural effects in this way yields an account which is plausible: the mental model assumptions are themselves realistic and they are then able to explain the roots of otherwise puzzling BOT trajectories.

6.1.2. Behavioural effects undermine model output

A second example considers one of the arrows in the framework and looks at behavioural effects occurring around (as opposed to merely within) a model. Moreover, it deals with issues and problems yet to be resolved in SD. To illustrate, as shown in Fig. 5 specific ideas from the mind map of Fig. 1 (left) are again located using the framework.

People may be exposed to an SD model, all of its structural details and its output. Nevertheless, there may be rejection of that modelling experience for a number of reasons.

It may be that the content of the model is unknown, a black box that is not trusted (a well-documented problem in OR simulation) or simply that the language in which it is written makes no sense to non-specialists (Pidd, 1992; Watt, 1977).

Alternatively, the BOT trajectories may be impossible to interpret. People are observed to confuse plots over time (X against t) with static bivariate plots (Y against X), or simply do not perceive time as continuously flowing but rather structured around a few events, making it impossible for them to comprehend standard BOTs (Hovmand, Yadama, Chalise, Calhoun, & Conner, 2010).

Perhaps structure and BOTs can act as the basis for theorizing alternative action – but there is no consensus about what insights can be gained. Even with consensus, perhaps the suggested action is unacceptable, being politically or culturally infeasible. These issues are acknowledged in SD (Homer, 2012; Lane & Oliva, 1998; Weil, 2007) and also explored in OR (Checkland, 1985; Checkland & Scholes, 1990; Eden & Ackermann, 1998; Eden, Sims, & Jones, 1979).

These behavioural effects are a challenge. If they are in play then SD models will not provide satisfactory explanations. To improve practice, these effects must be addressed. The emphasis on building models with clients (Andersen et al., 2007; Forrester, 1971; Lane, 1992; Richardson, 1991; Richmond, 1987; Vennix, 1996), ensuring 'glass box' models and 'face validity' of any structural assumptions (Forrester & Senge, 1980; Richardson, 2013), taking the time to build up the 'language' of SD using methods appropriate for different communities (Hovmand, 2014), or simply ensuring that models appear in easily comprehensible symbols with recognizable variable names (Richmond, 1985) are all attempts to address these issues. Nevertheless, there is more work to be done here.

Similar to the approach of these two examples, all of the specific effects of Fig. 1 can be located in Fig. 3. The difference is that the framework is a more coherent account of the process of SD and acts as a way of delving into SD research on these and other behavioural effects.

6.1.3. Other theory illuminates behavioural effects

The framework can help identify other theories that can contribute to SD. Consider the antecedents of behaviour as described by the attitude–behaviour model of Ajzen (1991). His theory of planned behaviour arose in the field of social psychology. It focuses on single behaviours (= actions) and sees intention, or the commitment to a future course of action, as the immediate antecedent of behaviour. The version in Fig. 6 takes the extensions of Rouwette, Vennix, and Felling (2009) and makes further additions. The figure shows how the intention to perform a behaviour

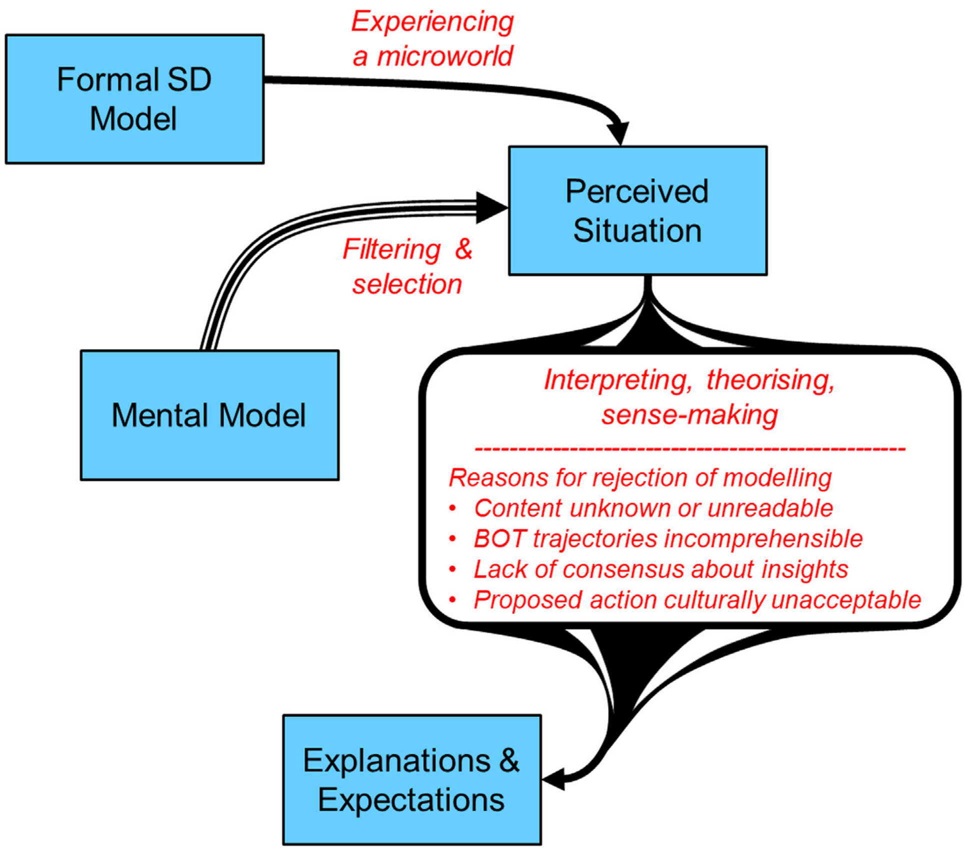

Fig. 5. Use of the framework to illustrate some of the behavioural effects that mean that model users might gain little from using an SD model.

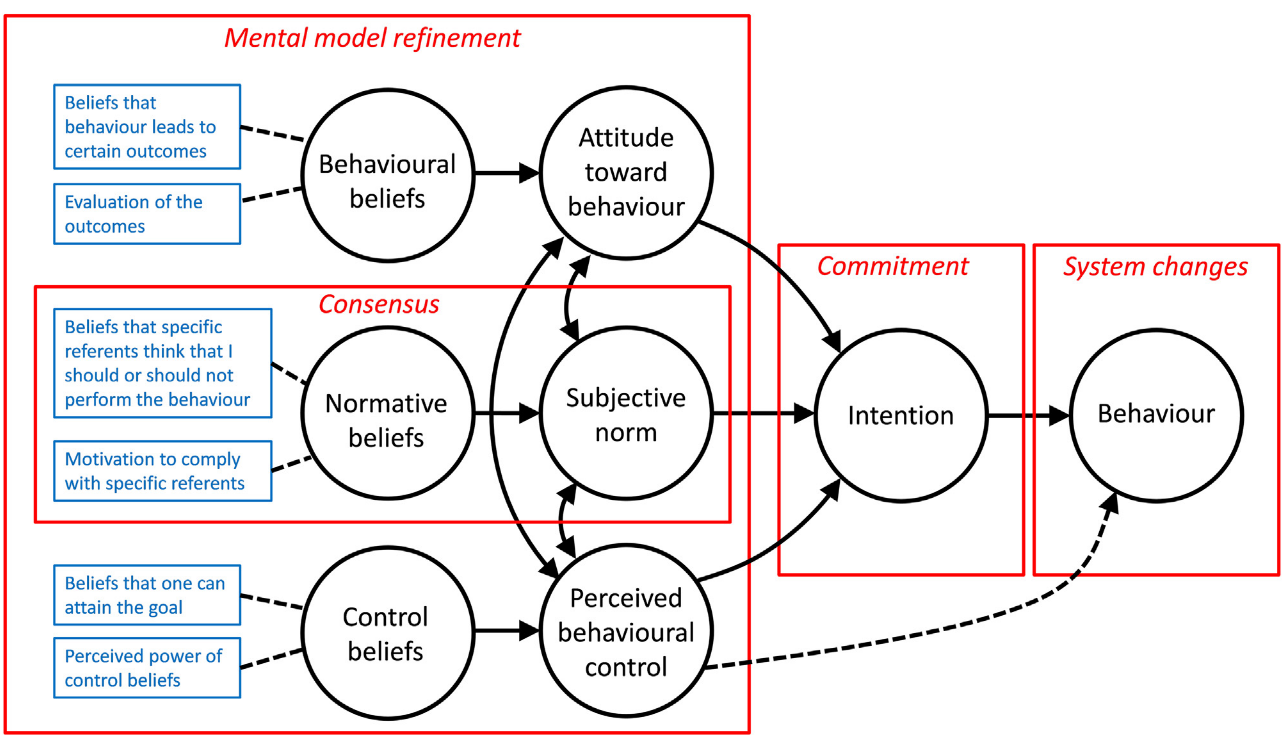

Fig. 6. Ajzen's theory of planned behaviour (1991) applied to SD by Rouwette et al. (2009) and the authors (see text for details). Note the plethora of 'behavioural effects' referred to. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

depends on three factors. First, attitude toward the behaviour, which captures the personal evaluation of a behaviour's consequences. Second, subjective norm, which refers to the opinion of others about the behaviour. Third, perceived behavioural control, the degree to which a person feels they can perform the behaviour. Each of these factors is in turn based on: beliefs regarding the strength between the behaviour and (respectively) outcomes, preferences of others and resources; and the evaluation of those beliefs. Solid arrows represent causal relations between concepts, the broken arrow the direct influence of perceived behavioural control on behaviour to the extent that perception reflects actual control. The broken lines connect measurement indicators to a related concept. For instance, behavioural beliefs are measured by a set of items on the strength of the relation between the behaviour and a particular outcome, and evaluation of that outcome. The boxes indicate concepts central to BehSD, ones that relate to behaviour and its antecedents as specified in the Ajzen theory.

Rouwette et al. (2009) see connections with the mental models ideas of Richardson et al. (1994) and argue for the relevance of the theory to group modelling. Certainly, when seen in the context of our framework, Ajzen's theory brings new ideas and insights. It unpacks and adds new features to a number of elements. What is meant by 'explanations and expectations', and how these lead to learning and a changed mental model, can benefit from the detail of the 'Mental model refinement' area. One can see more detail for our 'prompting and shaping' in Ajzen's 'Intention', and in how this leads to 'decision and commitment'. The theory also includes the processes of 'altering the world' in 'behaviour' that yields 'System changes'.

This is not a purely rational account of decision making; it contains norms, subjective values, concerning where one wishes to be and how one might get there. This theory therefore prompts further SD research on a rich pool of issues concerning these processes, a pool which relates to individuals' attitudes to the expected reaction of others, or to the emotional value attached to a particular course of action. On the second point, according to the Ajzen model, a more positive attitude, norm or perceived control will increase intentions and subsequently the likelihood that the corresponding behaviour follows.

This theory strengthens the case that behavioural effects are relevant to SD – the model is full of such effects. It also shows how tapping into a theory from another discipline acesses a whole body of experimental work that can illuminate some of the core activities in Fig. 6, activities that might seem a long way from dynamical systems theory - the mathematical core of SD - but which are actually central to using it in practical situations to improve decision-making.

6.2. General perspective on phenomena

The BehSD perspective defines the phenomena of interest, what the new stance encourages us to look at, or assume. It is introduced by reference to the concepts of 'problems' and 'messes', terms which relates to the move from Hard OR into PSMs (Ackoff, 1979; 1981) but which have been applied in SD (Vennix, 1999). With 'problems', interest centres on the physics of supply chains, factories, inventories and networks, or on the arithmetic of accounting. People are assumed to be perfectly rational, self-interested maximisers whose decisions use deliberation and logic. They are not 'judgemental dopes' (Coulon, 1995) but rather 'homo economicus' who can optimise the functioning of complex technical systems.

The BehSD perspective has it that whilst there are phenomena that are adequately described using these ideas, SD has always been concerned with situations in which other aspects relating to human beings are critical. Consideration of these 'messes' means taking into account the organizational/social context of those who might benefit from SD, taking into account the foibles, failings and idiosyncrasies of humans in social settings. People are assumed to be swayed by cognitive limitations, biases and social pressure, their decisions using short-cuts, biases, gut-feel and heuristics. They are 'Homo imperfectus' – yet the field of ethnomethodology would see them as 'accomplished social actors' who still manage to work together in groups to get things done (Garfinkel, 1967; Lane, 2004).

Note that the BehSD perspective is not dichotomously separate from previous ideas. Just as messes are an expansion of the concept of problems, the Venn Diagram of BehSD holds on to the 'technical' perspective as a sub-set but adds 'socio' elements to it. Being open to both can explain a wider range of phenomena, since; "the technocratic view is faulty, not because it is incorrect, but because it is incomplete" (Tinker & Lowe, 1984, p.45).

6.3. Axioms of BehSD

Five short axioms - statements that are taken to be true - together forge a definition of BehSD as we propose it in this paper. Behavioural System Dynamics is an approach to research in SD which involves the openly-declared, self-reflective project of applying the following axioms to advance the theory and practice of SD.

1) Firm acceptance that whilst a purely physical/mathematical approach can be powerful, it does not capture some critical aspects of many real world situations. Though derived from servo-mechanism theory, SD has always been concerned with the factors shaping individual decision-making and the role that modelling can play in a broader organisational and societal setting. In short, 'Two cheers for Physics; now think of the people'.
2) Wholesale engagement with theories, methods and findings from other disciplines. Whilst some SD practitioners have engaged with ideas from psychology, social psychology and sociology this is seen as rather specialist by many; that needs to change. In short, 'Stop dancing around the need to learn about and from other disciplines.'
3) Recognition of the value of natural, field and laboratory experiments. SD emerged in part from case studies; to progress it must develop a coherent and regularised body of empirical findings. In short 'Observe or run the experiment to get good data'.
4) Willingness to use (1) – (3) to create integrated theories. In SD the ultimate test of a model is the 'system-improvement test', better performance in the real system (Forrester & Senge, 1980); it takes the very best theories to help us pass that test and this is how to create them. In short, 'Mess management needs multi-disciplinarity'.
5) Commitment to use (1) to (4) as a basis for improving SD practice. A core belief of SD is that 'Life must be very practical … One works to get results' (Forrester, 1990, p. 2, also 1992a). BehSD may help to deliver those results.

In style, this definition is similar to Becker's (2016). It aims to be rich enough to embrace the range of ideas considered in earlier sections of this paper whilst being brief, clear and distinctive. Of course, these axioms are currently very general, the sort of features one would expect of well-posed, well-conducted scientific enterprises. Hence, as indicated, they possibly apply to BOR itself. Indeed, the axioms might also apply to the broader areas of agent-based modelling and simulation, both of which have implicit interest in behavioural issues. This generality indicates the pressing need to bring some structure to currently rather disparate explorations of behavioural effects in SD. This is itself a core argument of this paper and a core aim. For now, these axioms should be seen as giving direction at this early point of trying to define

BehSD, foundation stones necessary to formulate a more detailed theory. They set the standard that future work needs to begin to live up to. Our expectation is that as the emerging trend that we are calling BehSD progresses, its axioms will become more specific, indicating that the field is progressing in a coherent way, becoming, at long last, a normal science.

6.4. Promise of BehSD

Why make this effort? What does BehSD give? To answer this, consider Fig. 3 and the examples discussed in relation to this framework. There are three features common to all of those examples. First, there are unexpected but significant phenomena – perhaps they can now be called 'behavioural effects' – which are observed in practice, and/or observable in experiments. These are things that we need to know about (rather than be surprised by), things that must be taken into account. Second, there are theories which explain how and why the phenomena arise. Understanding 'why' is a core tenet of science. Third, there are suggestions - even if only embryonic suggestions requiring deeper research - for how to use those explanations to improve model-based interventions.

Using BehSD can illuminate all three features. Any system dynamicist looking at that list would surely see the promise and get excited. However, the last feature is key. In SD, explanation in itself is insufficient; its justification is that it offers a platform for improvement. Openness to behavioural phenomena, followed by observation and explanation based on inter-disciplinary theory building, can benefit SD practice. This is the promise of BehSD.

7. Closing remarks; moving forward with BehSD

This paper argues that behavioural concepts can be applied to SD modelling in a useful way. Whilst this paper cannot claim to offer a fully developed theory of BehSD, it advances the case for it. We close by reflecting on how that case stands in relation to each of the three criticisms of BOR raised in Section 2, and on how it should now go forward.

The first concern was about looseness of definition. This paper takes that head on, offering a definition (without 'behaviour' on the right-hand side) which draws on the material in Sections 4, 5 and 6.

The second concern was the breadth of phenomena considered. Our response is two-fold. The BehSD definition is certainly not narrow. However, the framework of Fig. 3 gives structure to its breadth by showing how different areas come together as part of the modelling process. Moreover, though broad, the definition is not without limits. Consequently, whilst the breadth of the current BOR project might be seen as 'imperialist' in nature – to use the term of Jackson (1987) - this is not be a concern for BehSD. The five axioms define its limits. If they cannot be applied then that area is not embraced by BehSD. Examples would include models of purely physical/ecological (Ford, 1999), or medical systems (Rogers, Gallaher, & Dingli, 2018): absent human interventions there would be no behavioural effects in these models. One can add the dynamical systems theory that is the mathematical core of SD (Groesser & Schaffernicht, 2012), the use of graph theory and eigenvalue analysis to find dominant loops (Kampmann & Oliva, 2006; Oliva, 2016), methods for model parameter estimation and calibration (Andrade & Duggan, 2021; Hosseinichimeh, Rahmandad, Jalali, & Wittenborn, 2016): the models being considered may contain behavioural phenomena but the analysis approaches are non-behavioural. This is still a large SD territory. Consequently, BehSD is no re-labelling project or flag of convenience for all of SD. Rather, it is an area still emerging, still defining itself:

> "The typical history of a concept, whether it be "chemical element", "atom", "the unconscious", or whatever, involves the initial emergence of the concept as a vague idea, followed by its gradual clarification as the theory in which it plays apart takes a more precise and coherent form." (Chalmers, 1982, p. 79)

This applies to BehSD. This paper offers a first step of clarification and coherence.

The third concern was the false sense of newness within BOR. This is not inherited by BehSD. Rather, the age of the general idea is acknowledged (see 3.3) and axiom (2) holds that something needs to be done to render coherent an already acknowledged bundle of issues and find a means of moving forward research related to them.

Moving forward with these ideas is a 'grand challenge' to SD. Arguably the field needs such challenge. Rouwette refers to its "apparent stagnation", references other SD voices in support, and suggests that "lack of theoretical focus may be added to the list of possible explanations for the low growth of the field" (Rouwette, 2017, p. 512). In response, he embraces earlier calls for an "embedded [SD]" (Rouwette, 2017) which draws on other social science methods in a manner similar to that proposed here. The field is not closed to challenge. Graham (2009) concentrated on application areas (indicating the practical focus of SD). A better example is Richardson (1996), many of whose ideas are related to those in this paper.

How can research that adopts the BehSD perspective go forward? One approach might be that of the Cochrane Institute: a systematic gathering of information about what is out there which then determines where to focus future work (Bero & Rennie, 1995; Grimshaw, 2004). This could start by selecting one of the arrows in Fig. 3, for instance the arrow connecting Explanations & Expectations to Decisions & Commitments. Following the Cochrane guidelines, a literature review conducted using keywords would generate the existing research outputs which have considered the relation between these two concepts, and how this relation is influenced by System Dynamics-based interventions. The examples provided in Section 5 give a first indication of the search terms to be used to identify relevant studies. Fig. 1 shows some of the phenomena of interest and Section 6.1 gives three examples of using the framework to identify previous work on specific behavioural effects of SD. However, applying this systematic approach for all of elements of Fig. 3 would start to build a theory of BehSD (Gregor, 2006); it would produce an accounting of what is known, and an indication of future research challenges - work still to be done.

What is clear is that this is a long-term project. Central to BehSD is the need for ideas and theories from other fields to make a richer theory for SD practice. That implies iteration between theory and practice, a lot of living with ideas, trying them out and

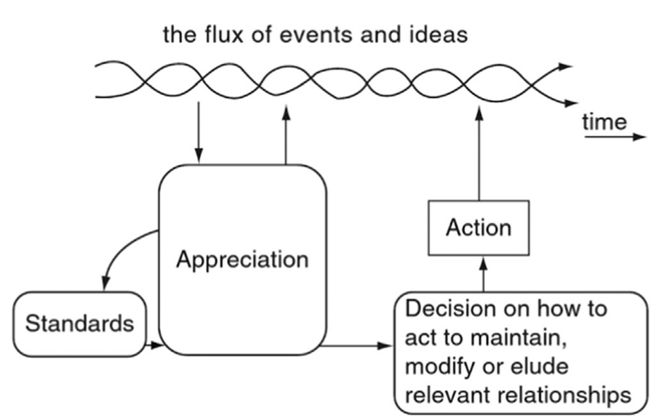

Fig. 7. Ideas and events intertwine in Vicker's 'Appreciative System' concept (Checkland & Casar, 1986). A similar approach is necessary to advance BehSD.

thinking about the results of applying them. The approach is described by Nonaka (1994) and is illustrated by Vicker's concept of an Appreciative System (see Fig. 7): ideas and events intertwining. Beginning such a process is hard. The problem has been stated thus:

> "You can't live in the world without an idea of the world, but it's living that makes the ideas. You can't wait for a theory, but you have to have a theory" (Kushner, 2015, p. 278).

BehSD is the project of applying the five axioms and watching how theory and practice intertwine, with the aim of improving the use of SD. This paper offers initial ideas for beginning to make this project a rigorous reality. The important thing is to begin.

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