System Dynamics: from Theory to Practice

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ABSTRACT *The title of this refers to the range of system dynamics applications. This range extends from use as experimental tools in theory development through to the practice of problem solving and investigation of real world behaviours. This paper takes a two-facetted view of the scope of and issues in system dynamics practice based on the author's personal experiences. The first derives from his role as Executive Editor of the System Dynamics Review, and gives an analysis and interpretation of the range of articles that have appeared in the journal in the recent past. The second facet is a practitioner's view of SD in practice, based on observations from his activities as an academic who consults and an erstwhile full-time SD consultant, and on the similar observations of others. These experiences point to a field where Forrester's original concepts have proved highly successful where they have been used in practical applications. Barriers to wider use have largely been in the mechanics of the implementation process. These are now being overcome by the latest generations of SD modelling software which are catalysing the rapid expansion in practice, but these too bring their dangers.*

Keywords: System Dynamics, practice, theories, publications

INTRODUCTION

The organisers of this conference, who kindly invited me to present a keynote paper, suggested a title which fitted well with the overall theme. I decided to go with it - I do not think they included a question mark at the end, so I have not either.

The title as stands may on first sight be interpreted as suggesting that over the years system dynamics has gone through a transition from being a theory or set of theories to a practical tool. I do not believe that this is a useful interpretation. The generally presumed story of the genesis of systems dynamics is that the ideas first suggested themselves to Jay Forrester as he sought to understand the practical problems of a company with a perplexing problem of fluctuations in their manufacturing/market system (only to discover their problems were actually caused by their internal processes). So was it then that system dynamics was really a theory that was born out of practice? This may be exactly as it was, or it may be that Prof. Forrester had already been juggling with theories in his mind. Whichever the sequence, it is clear that system dynamics emerged as both a set of theories and a practical tool very quickly, and very early on in its history.

The most useful interpretation of the title therefore that it really points to the 'scope' of system dynamics – the spectrum of use that can be made of its underlying theories. This spectrum covers the approaches grouped under the system dynamics banner being used as an experimental tool to support theory development, to their use in organisations to study and predict system behaviour, and/or in use in policy evaluation and strategy formulation. But also it should not be construed that 'practice' means business or management practice, as the ideas have probably been used across the widest variety of system types and subject disciplines of any analytical/decision support approaches.

This paper looks at the scope of the application of SD ideas from through development through to practical application in real world environments. It does this in two ways. Firstly as Executive Editor of the official journal of the international System Dynamics Society, the System Dynamics Review (SDR), I can review the field from the editor's chair. Secondly, the literature describes a very wide of SD applications, and this are compared with my own experiences as an academic who consults and someone who has worked in two consulting firms which used SD as their predominant analytical approach.

WHERE ARE THE BOUNDARIES OF SYSTEM DYNAMICS?

We must start with reference to the debate concerning the boundaries of system dynamics. There are two dimensions to this debate. Firstly, there is a view that the qualitative or 'soft' use of stock-flow and/or causal-loop diagrams to support feedback thinking in raising understanding of system behaviour and the 'intuiting' of future behaviour is not really SD. Practitioners may have used these approaches informally before, but it was Wolstenholme (1982) who first discussed 'soft' SD in the refereed literature. Some argue that this is an inadequate tool and that no real benefit can be obtained unless systems are actually simulated with sufficiently detailed models. In his recent comprehensive book, John Sterman (2000) titles a sub-section 'Why it is essential to simulate', and while he does present some counter-arguments he seems pretty unequivocal in his own view. Vennix (1999) gives a good balanced view of its potential value, and it could be argued that there is now a quantity of material in the literature of the field that claims significant benefit can be obtained from soft use of system dynamics tools alone. As this soft system methodology comes from feedback thinking and the capturing of mental models of system structure through the process plant analogy with stock-flow diagrams, or the derivative causal-loop diagrams, there is close proximity to the original SD concepts (Forrester, 1961). For me this approach therefore passes two key tests – analysis is based on feedback thinking concerning multiple causality, and benefit is obtained. It has been argued (Arthur and Winch, 1999) that validity of the model-based process, not just of the model, is the critical issue and this points to a fitness for purpose view of any model – quantitative or otherwise (see later). Indeed, Sterman himself has reported a business firm evidently benefiting highly from analysis based on soft use alone (Risch *et al*, 1995).

The second dimension, ironically, is at the other extreme. There has recently been exponential growth in the sale of SD software products, especially in the two very similar packages – iThink and Powersim – that use visual interfaces based on the stock-flow iconography for model development, and the third package, Vensim. All these packages are well developed and come with excellent support, including self-learn tutorials and training via the software suppliers themselves or third parties. Now comes the problem – should we consider as 'system dynamics' the use of these purpose-developed tools to study the behaviour of systems, even if the analysis includes no direct consideration of system behaviour in terms of feedback and structure?

Forrester (1961) emphasised the multi-loop, multi-state, non-linear character of the feedback systems in which we live, and it follows therefore that system dynamics entails analysing their behaviour as such. It could therefore be argued that analysis in absence of explicit reference to these aspects is not SD, but simply the expedient use of a convenient software tool. On the other hand, the software will only work if the model involves an integrated stock-flow (or multi-state) structure with feedback to control rates of flow. Also, can we know whether or not the analyst is subliminally applying feedback thinking in his/her interpretation and extrapolations. Regrettably, some of the articles submitted to the SDR and seen in conferences contain fundamental errors in equation structures or dimensions, for example, that must have meant the analyst had no real understanding of the nature of feedback structures and of the relationships between stocks and flows. Yet these still confidently present important conclusions, and one has to challenge that their false basis means that they are not 'system dynamics', nor frankly even acceptable science.

THE SCOPE AND ROLE FOR SYSTEM DYNAMICS APPLICATIONS

The System Dynamics Review[1] has been shown to be the major specialist source of information for SD practitioners, or at least those practitioners who are members of the SD Society (Scholl, 1995). In terms of how the approach is presented to these people, the Review is therefore a reasonable yardstick to use. (Many, of course, also reported reading other specialist operational research, management science, and systems journals, as well as publications concerning business and other specialisms.) To this end a quick analysis of the articles published since the author became Executive Editor in 1995. The articles were scanned for:

1. Author affiliation.
2. Whether the article specifically related to 'hard' or 'soft' use of SD methods, or 'gaming'.
3. The nature of the content – Methodological, Use of SD methods as a research tool, Case study; Practical processes, advice, problems, learning issues: and Other (including review articles).
4. The article context – Business operations; Business strategy/policy; Public sector, community, not-for-profit; Macro-level systems: social and macro-economic; and Natural and technological.

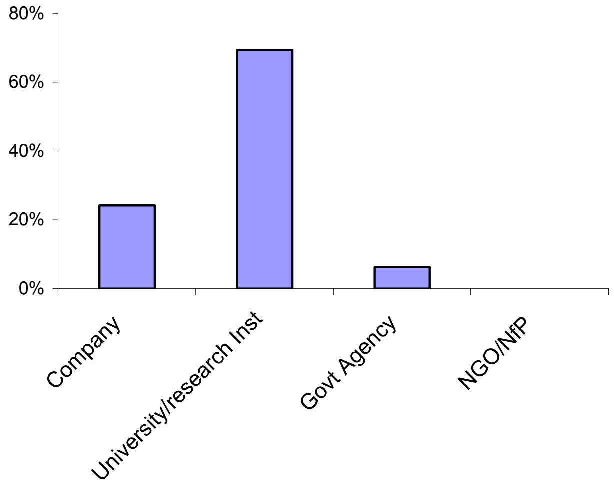
The categorisation was done purely on the author/editor's personal judgement, and attempted to reflect the articles' primary foci, though many obviously overlapped in some respects. A total of 88 articles appeared in the issues examined.

In terms of authorship, a full 75% of articles included at least one author with a university or research institute affiliation (see *Figure 1*). A high value is hardly surprising as publishing is an academic way of life, and academics have most interest in publishing their work. On the other hand, it was also revealed that around a

[1] The System Dynamics Review (ISSN 0883-7066) is published quarterly by John Wiley and Sons and is the official journal of the System Dynamics Society. Details on: www.interscience.wiley.com.

third (33%) of articles were authored by practitioners or included at least one practitioner in the authoring team. Of these practitioners, 23 (26%) out of the 29 were in companies or business consultancies – suggesting therefore that over a quarter of all articles directly reflected a practising businessperson's viewpoint. Very interestingly, a total of only six articles (7%) included authors from government agencies, and in fact none reflected non-governmental organisations (NGO) or not-for profit enterprises (Though, as will be seen later, a

Figure 1 - Author Affiliation

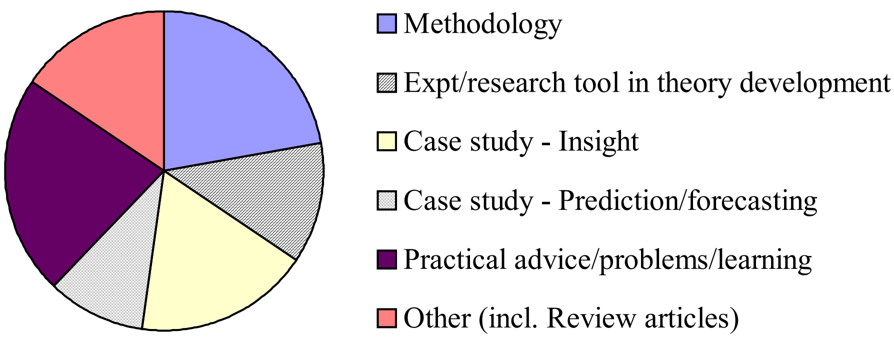


significant proportion of articles related to issues in the expected spheres of interest of these groups.) Obviously, and fortunately, there are occasions when those in full-time practice wish to showcase their work.

Earlier, it was maintained that 'soft' use of the techniques (that is, the use of the diagramming tools for understanding structure and of feedback thinking to interpolate behaviour) should be legitimately considered as system dynamics. Seventy of the 88 articles directly involved the use of SD models (the remainder concerned practical issues of a non-specific type or mathematically based argument). Of these, the clear majority – 74% – explicitly concerned quantitative modelling, with a further small proportion - 7% - involving SD gaming, which also has quantitative models at the core. Consequently, only a fifth of these articles referred to soft methods. No attempt was made during the analysis to interpret whether benefits or other aspects of soft use may also have been considered in the fine detail of those articles where the clear primary focus was on hard use.

The content of the articles (see *Figure 2*), at least from the Editor's viewpoint, exhibits a satisfyingly wide

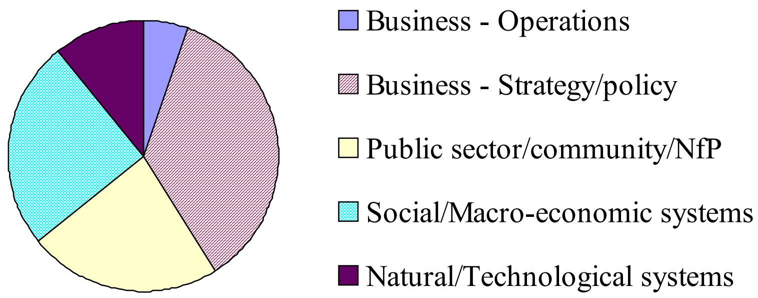
Figure 2 - Main Focus of Article Content



and even range of theme, as called for by the journal's objectives. 'Methodological' articles represent 22% of the content themes mentioned, the equal largest sector. That methodology ranks high is hardly surprising, though interestingly this is significantly lower than the 35% of journal pages observed by Scholl in his 1995 analysis. It is unlikely that methodological articles are generally longer than other types, this may therefore reflect that Scholl was reporting readers' perceptions, or that there has been a shift towards other article types in the more recent past. In addition to articles focussing on SD methodology, a further 12% describe the use of SD methods to develop or test theories about other aspects of system behaviour or performance, for example, production processes and sustainable development. While probably of practical importance in due course, these have been categorised separately from articles which relate to current practice. Three of the categories did relate directly to practical aspects: two case study categories - those where system insights were sought, and those where the primary intention was quantitative analysis, prediction or forecasting – and those relating to other general practical issues, application processes, advice, problems and learning aspects. In total these represent a main focus in fully a half of all articles. In addition, some of the review and other articles are likely also to have relevance to practice.

The last categorisation related to the primary context of articles. Around a third of articles were not specific, many of the methodological, and some of the practical issues and 'other' category fell into this. The remaining

Figure 3 - Application Context



56 articles were broken out as in Figure 3. Just over 40% of these articles related specifically to business issues; of this, the vast majority concerned strategy/ policy rather than operational aspects. Approximately a quarter of articles related to each of the 'Public sector/community/ NfP' and 'Social/Macro-economic systems' categories, whilst the remaining 10% or so related to Natural and Technological systems. An interesting observation from this is that there is a 60/40 split in terms of non-business versus business practical articles, yet only 6 articles in the former category were authored or co-authored by employees of government agencies, and none at all by employees of non-governmental or not-for profit organisations. It would appear therefore that given academics comprise the largest authorship group but obviously contribute in a significant way to practice articles, they have a greater influence in non-business than in business applications.

THE PRACTICE OF PRACTICE

Of course, a survey of the articles in System Dynamics Review by no means tells the whole story. While SDR is aimed at the mixed academic/practitioner membership profile of the society, the balance in its authorship is unlikely to be representative of even the membership balance, let alone of the wider population of SD users. Scholl (1995) reported a split of 45% of respondents being academics, with 18% as management consultants, and 11% practising within a business organisation (the remaining 26% was not reported). He also commented that around a quarter of academics also had to be practitioners to balance the application statistics.

However, it is very likely that there are many more practitioners using SD effectively in business firms and consultancies who are neither Society members nor SDR authors. Indeed in terms of consulting firms alone, McKinsey & Co. and other business consultancies, including the major accounting/consulting firms, have been building significant SD capability over recent years. This is in addition to the specialist software firms who followed Pugh-Roberts' lead and offer consulting services alongside product sales, and the many small specialist practices. It is believed there may also be significant communities of SD practitioners in other fields, like ecology, where there is a tradition of dynamic system analysis and feedback thinking, even the use of SD-based software, but whose results rarely appear in the Review. System Dynamics Review itself does not distinguish itself specifically as a management/business journal (though it is highly ranked internationally in the Journal Citation Reports[2] in that category), and submissions in any other fields are strongly welcomed. My own experience of SD in practice is in the business field, and I shall orient my comments that way.

[2] Journal Citation Reports are published annually by the ISI. They analyse references or citations to journals appearing in the previous year's Science Citation Index (SCI) and Social Science Citation Index (SSCI). By counting authors' citations journal by journal and for how long articles are cited, they give a measure of the relative influence and impact of the various journals. SDR ranked #28 worldwide in 1998, and #15 for 1997 citations in the 'Management' category. Details of the ISI and JCRs may be found on: http://www.isinet.com/isi/products/citation/jcr

Around ten years ago, I was asked to write about SD practice, specifically from the business consultant's viewpoint (Winch, 1991). In looking back over the range of consulting assignments I had then undertaken (which I was pleased to be able to report as all being successful), I attempted to characterise the projects and their circumstances. All the projects at that time involved quantitative modelling, usually with large, detailed models. The common features of the projects were considered, as they would have appeared at:

1. the project proposal stage;
2. as the project proceeds;
3. in retrospect.

Looking at these projects going in, they would have tended to concern industries experiencing significant structural change – rationalisation, new alignments/joint ventures, and emergent technologies. The context also covered highly complex industries or situations where the clients' managers acknowledged that they could not fully explain what had happened, or predict what would happen. These characterisations probably describe exactly the circumstances where SD – 'hard' or 'soft' usage - is going to score over other business analysis techniques.

At that time too, an internal advocate seemed critical, and that it had to be demonstrated that SD had something special to offer to the analysis – the approach itself was not well-enough known for it to sell itself. It is probable now that where the larger specialist SD consultancies and the likes of McKinsey and PriceWaterhouseCoopers are involved, it will be rather easier to persuade clients that this is the best approach. Another observation made at the time was that our clients appeared typically to be firms with a culture of research and innovation, these seemed more able to accept the potential of the relatively novel approach. Again, and for similar reasons, this is much less likely now to be the case.

During the project progress phase, a common characteristic was that projects typically involved phased progress, with results and analysis, conclusions and benefit to the client at each phase. Lyneis, 1999, has similarly described a phased process that he and colleagues at consultants Pugh-Roberts use for SD studies. This approach actually involves a three phased progression initially involving 'systems thinking' – 'timepaths', causal loop and stock-flow diagrams, and mental simulation, then a phase using a simple 'insight' simulation model, before finally advancing to a fully detailed model. Another common characteristic was that the models were often developed incorporating existing formulations or generic modules, which represented an efficient process. SD models, particularly large ones, tend to be relatively expensive to construct even if the likely benefits are similarly high. Efficient model development tools are important therefore to permit the costing of such models at reasonable levels. Besides the use of fragments of earlier models, various other approaches have now evolved to enhance model development efficiency: the graphic-interface packages permit a rapid transition from diagram to code, Powersim has for some time been demonstrating a 'component'-based approach to modelling gas-distribution systems, and a 'Computer-aided Visioning (CAV) system has been developed at Plymouth which uses a simple-to-calibrate generic change model (Winch, 2000). These factors also add to another dimension, which is that while SD studies must have participation and support at very senior levels in an organisation, the processes must not be 'time-demanding'.

The final common feature was the presentation to clients of a compelling argument for the validity of the quantitative models. Model validity is one of the critical areas at the interface of methodology and practice and has attracted much attention recently in the literature. All model-building textbooks and guides emphasise the point, with the list by Forrester and Senge (1980) for a long time being seen as the foundation for most validation procedures; more recently, Barlas (1996) has updated and reviewed this list. Coyle and Exelby (2000) discuss the very serious view of validation taken within the consulting firm in which they operate, and compare critically the differences between validation for commercial clients and validation for academic purposes. They describe a multistage validation process involving upwards of seventy-five different tests, though for commercial reasons the full details of these test are not divulged. Arthur and Winch (1999) have also considered validation, but in the context of the whole modelling intervention. This proposes a three-dimensional view of validation with scales reflecting the different dimensions of the whole model-based intervention:

a) ***substantive*** (technical content or perceived representativeness of models)
b) ***constructive*** (process effectiveness or learning by participants)
a) ***instrumental*** (outcome or final utility of the project or intervention validity)

With this essentially fit-for-purpose approach, models used in detailed evaluations, for example, would have to score highly on the *substantive* scale, but not necessarily on the *constructive* scale; 'insight' type models would have to score much higher on the *constructive* and possibly the *instrumental* dimensions, but the technical, *substantive,* content of the model could be very low.

Finally, in looking at the project experiences in retrospect, two key common features seemed to emerge. Firstly, while the projects were all primarily concerned with predictions about medium/long term dynamics in the wider system and/or evaluations of specific strategic options, in many studies the building of consensus in the executive teams was a major actual benefit to clients (Winch, 1993). Many people have used soft SD as a way of consensus-building, and procedures and protocols have also been developed specifically for the task of working with teams, as opposed to individuals, in the development of formal models. The leading text on this is by Jac Vennix (1996) which gives a full coverage of the processes and his experiences of them working with teams on practical assignments. He also co-edited a special issue of SDR on this topic (SDR13:2, 1997) in which there is also a practical guide to using scripted techniques – 'scripts' – for implementing team-based approaches (Anderson & Richardson, 1997).

The second common feature was that while an intention had often been to leave clients with working models which they could then use on their own for further analyses, in reality this rarely happened. Partly, this was simply because the models fitted the specific situations and once the decisions had been made, clients felt no major motivation to maintain them in working order. Other factors were that using these earlier models was not particularly easy, even when front-end interfaces were constructed, and that those in the client firms with experience of working with the models quickly moved up and on. There is no doubt that the advanced 'flight-simulator' type interface functionality in the leading packages that enables quick parameter changes and set-up of scenarios, and the easy-on-the-eye visual outputs, means that there is now a much higher probability of non-specialists continuing to work with models over extended periods.

WHERE THEORY HAS NOT YET BECOME PRACTICE

There are areas where theoretical advances in the field have not yet manifested themselves in practice to any degree. The first is deterministic chaos and the second optimisation.

Chaotic behaviour in deterministic, non-linear systems – as those studied with SD typically are – has been observed and researched over a number of years. Research interest in this area peaked in the period 1988-91 with the SDR included a special issue on this topic (System Dynamics Review, 1988), and some texts have included significant sections on this dimension (see for example Stacey, 19XX). Relatively simple systems like the ubiquitous Beer game can produce chaotic behaviour under certain circumstances (Sterman, 2000; Mosekilde, 1996), yet I never recall seeing anything like chaotic behaviour when I have run the game, nor heard others recount such an experience. Some attempts, though these are not identified as system dynamics, have been made to apply chaos 'theory' in business problems, typically in the 'holy grail' area of stock-market forecasting, though these have usually foundered because the vast quantities of data required to establish the models simply do not exist. This is likely to remain a reason why chaos within SD will also remain substantially a theoretical aspect for the foreseeable future.

The combining of simulation with optimisation within system dynamics is another area yet to break into mainstream modelling. I believe I can claim to have been the first to do this in my own doctoral studies in the mid-seventies (Winch 1977, 1979) when a tanker-chartering model was embedded within a NAG hill-climbing algorithm. The objective was to find the 'optimum' levels of forecast bias in the system that would lead to minimum tanker-chartering costs over a defined period. That was purely as a research technique intended to investigate how robust systems might be with regard to forecast errors. These ideas were carried forward, largely by the Bradford group and its collaborators (Coyle, 1992, 1997, Dangerfield & Roberts, 1996), as a potential policy search process. Keloharju (1983) pioneered the direct linking of SD models to an optimisation routine within simulation software by creating a facility to integrate this with the DYSMAP modelling package; this functionality remains within the COSMIC/COSMOS, though these packages are in very limited use. Interestingly, Powersim has evolved now to include an optimisation facility in the SOLVER module which interfaces with its CONSTRUCTOR product. With this product it is argued that model calibration can be aided by using this functionality in the search for optimum parameter values to achieve best fit to historic data, and also in the search for optimal policies.

However, Coyle (1997, p.317) himself cautions; 'Optimisation is strong medicine and must be used intelligently'. Clearly, the process, which Coyle describes as 'optimisation by repeated simulation', can be seen as simply speeding up and enhancing the manual search that analysts would have to undertake to identify preferred outcomes through their own cycles of repeated simulation of their models. But here again we face the problem that, if the search process is fully automated, then the conscious use of 'feedback thinking' may not be taking place - in which case, is this system dynamics? Coyle emphasises that using such processes can lead to greater understanding, especially about limits, and also to an enhanced appreciation of system objectives. It has to be said that for some this is not even strong medicine with a high risk of over-dose, but is rather snake-oil. Certainly if one believes that the modelling process is more important than the end model, which is claimed in many studies, then moving to a less hands-on and less transparent analysis procedure is likely to be counterproductive. It would certainly seem that if used injudiciously, the scope for powerful software leading to meaningless, or, worse, simply wrong answers could be greatly enhanced. The use of the new Powersim functionality is beginning to be reported (Hovmand, 2000), but it does remain to be seen if it will become a widely used tool in practice, even now that the mainstream SD software has incorporated optimisation functionality.

CONCLUSIONS

This paper has argued that system dynamics is a set of ideas and theories that has already established itself as a powerful practical tool. It was not born out of obscure mathematical theories, but out of the practical, if then innovative, idea of applying engineering feedback principles and computer simulation to industrial and other systems. Right from the start these were seen as offering new and maybe unique opportunities to address real world issues. For many years the approach remained largely in universities, though many professors were active as consultants, students used the approach in their thesis work in companies and other outside organisations, and some went on to influential if rather isolated careers in organisations or consulting. Two major trends in the last decade have rapidly expanded the use of this approach outside academe – the widespread availability of graphics-based software tools, and the development of SD capability by the world-class business consulting firms.

The survey of recent materials in the SDR, albeit limited, has shown that a majority of publications are strongly practical in outlook. It would appear that the proportion of space devoted to methodological aspects has reduced by a significant margin in recent years. The approach seems to be well established now as a powerful aid in business policy/strategy development, but also has been widely applied in the management and understanding of social, macro-economic and community-based situations. It does appear though that while the trend is for business applications to be undertaken more and more by consultancies or firms themselves, non-business applications are more likely still to involve academic institutions in the work. Healthcare is one area that has already seen a significant number of applications (see, for example, Dangerfield and Roberts, 1999) and further expansions in this group and in other public/civic services are also likely to become much more prevalent. This will be accelerated as the large consultancies extend their practices in these sectors.

There has never been a divide between system dynamics theory and practice in most respects. My own experiences have largely been with highly detailed models developed for quantitative evaluations and longer-term industry outlooks. These have been successful in these primary objectives, but have also produced the highly valuable by-product of consensus building. A critical issue in such models has always been validation, and recent writings on this are beginning to take a practical view of what constitutes process validity, rather than model validity *per se*. The fact that validation processes could be quite different for interventions with different objectives, and different for commercial clients versus academic audiences is also being recognised.

The major barriers to a wider spread application of SD in practice in the past have been the time taken to develop detailed models, the need for model-builders who could combine high context (e.g. business) awareness with code-writing skills, the difficulty for non-modellers to join the model development process, and the difficulty for those left with the models to use them after the specialists had left the scene. These were problems with the mechanics of the intervention, not with the approaches themselves. Where SD had been used in practical situations it had had a pretty high success rate. Recent developments in the leading software products are beginning to overcome these mechanistic problems, and largely account for why the approach is now more rapidly than ever establishing itself as the critical approach for strategic analysis against the dual challenge of structural and dynamic complexity. These tools can make the model-development process much quicker and more accessible to non-modelling specialists. However, there is still a need for further programmes of education and training to ensure that there is an increasing flow of knowledgeable practitioners who are able to prevent the potential misapplication of these powerful tools by inexperienced, incompetent, or lazy users of the software.

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