An opportunity for system dynamics in manufacturing system modelling

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1. Introduction

The manufacturing systems operating within today's factories are invariably complex. Attempting to design or redesign these systems can be an awesome challenge for practising managers and engineers. In this situation, computer simulation techniques can be very useful. A survey by the Simulation Study Group (1991) revealed that whilst applications of simulation in the UK manufacturing industry had not been widespread, those companies which had employed this technology had expressed satisfaction with its effectiveness. There are two principal types of computer simulation techniques, i.e. discrete event and continuous. Discrete event simulation (DES) is, according to, e.g. Carrie (1988), usually used to build models in the manufacturing industry. However, there appears to be a lack of current citations which advocate the continuous simulation technique. This is particularly intriguing as one form of continuous modelling, system dynamics (SD), was originally favoured for industrial modelling (Forrester 1958, 1961). On this basis, we are keen to establish whether an important opportunity for efficiently modelling manufacturing systems is being overlooked.

The aim of the research that is reported in this paper has been to establish whether SD has declined in popularity as a modelling approach, or alternatively whether there are pockets of inactivity in an otherwise expanding discipline. To achieve this aim, this paper presents a structured literature review that has established the current status of SD application. In particular, the paper describes where SD modelling has grown in importance, and conversely, areas where it has declined. This investigation has clearly shown that SD is being actively applied in areas, e.g. ecological modelling, but that comparable levels of activity are absent in industrial modelling. Therefore, in this paper we attempt to understand why this has occurred, and whether this represents a missed opportunity.

The paper is structured to first describe the technique of SD modelling. A structured method is developed and used for classifying recent literature about the application of SD. This leads to observations on possible directions for future SDresearch, particularly in terms of the applicability of the technique to manufacturing systems modelling.

2. The origin of SD and its application to manufacturing systems modelling

The principles of SD were developed in 1956 at the Massachusetts Institute of Technology by Forrester (1961). He introduced his ideas in Industrial Dynamics, and launched his thoughts as a 'major breakthrough for decision makers' (Forrester 1958). Applications of the method spread into the social sciences area (Forrester 1975), and as a consequence Forrester re-named the technique 'system dynamics'. He considered SD to reflect a universal applicability to any situation which can be modelled as a 'system', which combines people and/or machines (Towill 1993). Since this early conception, many contributions have been made to the SD field, as discussed later in this paper. The basic principles of SD are succinctly summarized by Wolstenholme (1989, 1990).

Wolstenholme considers SD to exist in both a qualitative or quantitative form. Qualitative SD consists of diagrams (causal loop or influence) which represent the system under study by means of various 'resources' which flow through a variety of 'states' according to 'rates'. The resource may be either physical (e.g. the flow of material, money, people, etc.) or non-physical (e.g. knowledge or motivation). The state (sometimes known as level or stock) is defined as any accumulation of resources which is relevant to the concern. Often, the states are clearly recognizable, e.g. inventory in a manufacturing system, cash balance or less obviously the labour force. They are the measurable quantities of any resource in a system at any point in any time, and the measurement is the unit of resource. States continue to exist even if all the system activity ceases. The resources flow through the system as the result of a driving activity which converts the resource from one state to another. Such a driving activity is represented in SD by rate variables, which are control variables which increase or deplete resource levels directly, and their dimensions are units per period of time, i.e. they control flows into and out of stock. As an example, in a manufacturing system, the stock of a product is affected by the flow rates of production and sales. These flow rates vary continuously and must be represented in such a way as to capture this variation.

System dynamics can be considered to be a method of system enquiry, and as such occupies a position between the sciences of operations research (OR) and 'systems thinking' (a philosophical approach) (Checkland 1981, Wolstenholme 1990). In considering how SD could be related to these 'hard' and 'soft' sciences, Keys (1988) concluded that the exact position of SD remained unresolved, but maintained that it is possible for scientists in both fields to relate to it. SD may also be considered in the sense of servomechanisms (the control systems view) and cybernetics (organizational/human systems structuring for problem solving) (Tustin 1953, Pidd 1992). Towill (1993) believes that advocates of either viewpoint would benefit from an understanding of both the 'hard' and 'soft' perspectives.

System dynamics met with some criticism in its early days, most notably from Ansoff and Slevin (1968), who queried the validity of the theory base applied by Forrester. To his credit, Forrester reiterated the theory published in Industrial Dynamics (1961) and pointed out that his models were not absolutely complete. Ansoff and Slevin's article is particularly relevant as it represents one of the earliest examples of an independent review of SD. The review highlights the rapid development of SD at that time, for Forrester pointed out in his response to Ansoff and Slevin (Forrester 1975) that much work had been carried out which was yet to be published, and this research had not been available to Ansoff and Slevin when writing their critique of Forrester's work.

Pidd (1992) identifies two main problems with SD in the early years: the mathematical equations were too complex to be understood by managers. However, Forrester foresaw in his early work that the development of the computer would aid the application of his technique. Now the equations may be solved rapidly whilst being hidden behind a user-friendly graphical interface, e.g. STELLA (Peterson 1992).

In terms of manufacturing applications of SD, a conceptualized model of a manufacturing system is outlined by Parnaby (1979). Likewise, by Byrne and Roberts (1994) who use SD to evaluate manufacturing performance in a kanban-based system. Towill has long been an advocate of the value of Forrester's work, and much of Towill's research activity has been involved with developing the Forrester supply chain models (Towill and del Vecchio 1994). Edghill and Towill (1989a,b) have, e.g. developed a generic library of control theory-based models of manufacturing systems. They argue that these models fulfill the criteria of being meaningful and comprehensible, as these three components give the holistic view that a manufacturing manager requires. Similarly, Baines (1994) considers the respective merits of DES and SD for evaluating the effect of proposed changes to a manufacturing system. He argues that although DES seems to give more credible models due to the level of detail that can be included in such models, SD model building times are considerably less. Baines argues that when considering strategic issues within a manufacturing company, then SD has some distinct advantages over DES.

These latter examples of research into SD applications in the manufacturing industry show that the original intention of SD as a dynamics-based industrial modelling technique is still relevant. However, if a similar review was conducted of DES-based literature, then many more authors are apparently actively addressing research issues, e.g. Roth (1987), Thesen and Travis (1989), Law and Kelton (1991) and El Maghraby and Ravi (1992). This disparity in research activity is intriguing, and has led to the review described in the following sections.

3. Structuring an assessment of SD research

A structured approach is necessary in order to precisely examine whether the application of SD to manufacturing system modelling has been neglected. Such an examination can be made by comparing the current research activities across a range of SD applications, and trying to identify particular areas of strength and weakness in research progress. To carry out such a survey, a number of issues need to be addressed, in particular the breadth, age and source of literature that should be considered. Wolstenholme (1991) classed existing work by presenting a list of applications from SD Review during the late 1980s. In many ways, this paper aims to update and broaden

Wolstenholme's review of the late 1980s. A similar review to that of Wolstenholme would be solely based on SD Review, of which only five additional volumes of the journal are available from1990 onwards (volumes 6– 10, which cover 1990–1994). With only two or three issues per volume, there are not sufficient papers for a rigorous review. Furthermore, many of these articles are concerned with developing the methodology of SD, rather than exploring its applications, and hence are outside the scope of this review.

Further sources of papers do exist, and these are apparent on CD-ROM databases, e.g. Compendex (Dialog On Disc Compendex Plus 1998), Inspec (ProQuest Inspec Electronics and Computing (IEE) 1998) and IMID (Institute of Management International Databases Plus 1998). Searching through such a literature source is initially less productive than using journals dedicated to a subject, but is eventually more rewarding as a wider and probably more representative source of literature will be discovered. Hence, this research has employed this approach, considering a wide variety of research journals from 1990 onwards.

Having established the literature sources, it is necessary to establish a method of categorizing the contributions in the literature. Research contributions can initially be classified according to the industry with which they are associated, either primary, secondary or tertiary (or, alternatively, resources, manufacturing and services). Furthermore, they can also be classed in terms of the level at which they deal with an organization, e.g. operational, business or global level. Hence, two axes are apparent from which a table may be formed. Four columns can be chosen to represent the sector of industry in which an application is rooted, and these are as follows.

- Resources=primary industry, including agriculture, oil, and other natural resources, including ecological studies.
- Manufacturing=secondary industry, including assembly, production, project management and engineering design. •
- Services=tertiary industry, including software, health, transport.
- Any=a general business application which could be rooted in any sector of industry.

Likewise, three rows can be chosen to represent the scope of the situation modelled in an application, and these are as follows.

- Operations level=dealing with manufacturing system modelling, production planning, operations management, etc.
- Business level=dealing with business planning, forming strategies, testing, marketing and nancial scenarios. Also, corporate planning.
- Global level=dealing with political policy, national strategies, world issues.

On this basis, 12 categories are apparent that can be used to broadly group articles in terms of scope and sector.

4. A pplying an assessment of SD research

Through the application of the process described above, 80 papers have been identi ed and reviewed. Each of these papers has been subjected to a thorough examination in order to understand the subject matter and determine the industry in which each application is rooted. To ensure consistency between categorizations, the articles were read progressively, and earlier papers were then revisited and their classi cations checked and occasionally revised. At the end of the classi cation process, the scope and sector of each paper had been established. The results were thus collated into the 12 categories shown in gure 1. In order to illustrate how a speci c application from a paper was categorized in terms of a sector/scope placing on the framework diagram, some examples of categorization are given as follows.

Example paper 1: Wolstenholme, E. F., 1993, Case study in community care using systems thinking. J. Opl. Res. Soc., 44, 925–934.

Health care industry. Using an application of SD qualitative models in community care, Wolstenholme studies hospitals in terms of businesses at a community level, in order to understand the political in fluences and outcomes. The paper claims to reinforce the role of SD as a framework for strategic debate. This paper has been placed in the sector category for service industry. The scope of the study was interpreted as Business level.

Example paper 2: Towill, D. R. and del Vecchio, A., 1994, The application of filter theory to the study of supply chain dynamics. Production Planning & Control, 5, 82–96.

Production management: This paper by Towill and del Vecchio discusses supply chains within factories (one of the original applications of Industrial Dynamics). They are working at the 'hard' end of SD, as they are applying engineering systems theory (electronic filters) to the supply chain problem. Factory operations are of concern, so the paper is classified as manufacturing sector. The treatment is at a very detailed level so the scope classification is Operations.

Eighty papers have been classified according to the approach illustrated above. A summary showing the distribution of articles is given in figure 1.

Sector

Scope		Resources	Manufacturing	Services	Any level	Total
	Global	24	1	7	2	34
	Business	4	6	11	11	32
	Operations	3	8	3	0	14
	Total	31	15	21	13	80

Figure 1. A categorization of published papers (1990–1995) on the basis of sector and scope.

5. Categorization of research articles

Taking each of the 12 categories in turn, the key findings from the framework classification are as follows.

5.1. Category 1: Global/Resources

The high proportion of papers in this category is mainly due to the large number of publications dealing with ecology. The increasing concern from the late 1980s for the protection of the environment and its natural resources has led to much research in natural sciences, wildlife and pollution. Whilst these ecological applications are not directly linked with industry, other papers in the category discuss agriculture, e.g. Matthews and Hunt (1994), who modelled the growth of cassava. Predictions for the depletion of natural resources, e.g. coal, oil and gas, have been modelled by Naill et al. (1992), who presented a SD application for national energy policy planning. Also within the scope of the Global/Resources classification are papers dealing with the economic development (on a national scale) of the 'third world' countries. The SD Review was particularly rich in such applications during the period studied.

5.2. Category 2: Global/Manufacturing

Only one article was placed in this category, a paper by Chambers (1991) dealing with technology changes in the chemicals, fuels and energy sector. It could be argued that this paper might be classi ed as Global/Resources, but it has been placed in the manufacturing sector as it predominately deals with processing technology within the chemical industry.

5.3. Category 3: Global/Services

Some of the issues discussed in papers falling into this category are similar to those in the Global/Resources classification, as they deal with the effects on a country's economy. However, in this case such issues as transport systems and medical practices are discussed. For example, Abbas and Bell (1994) evaluate the applicability of SD to the modelling of the relationships between the different parts of a transport system and its environment, concluding that SD eases the testing of alternative transport- related policies.

5.4. Category 4: Global/Any

The papers in this category have been placed so because of a difficulty in placing them elsewhere. These papers discuss the introduction and subsequent success/ failure of products or services into world markets. Such papers may be described as technology management or corporate strategy. The techniques have equal applicability to products and services, and hence could be used in both the manufacturing and service sectors. As neither was specified, the papers have been placed in the 'Any' category.

5.5. Category 5: Business/Resources

This category is concerned with the individual business aspects of agricultural or energy industries, e.g. the issues surrounding pig breeding (Faust et al. 1993). Also in this category are papers dealing with socio-economic development on a community scale, e.g. the religious order examined by Gaynor et al. (1991) who analyses its policies. Furthermore, where resources were treated in a business planning sense, the research was placed into this category, as was the case with Zimmerman (1993) who assessed SD as one of a number of approaches to integrated planning which may be used in least cost integrated resource planning (LCIRP) for energy production, distribution and consumption.

5.6. Category 6: Business/Manufacturing

This category contains applications relating to the management and organization of production, e.g. manufacturing system modelling. Such work has been discussed in more detail earlier in the paper. The work in this category has a link with the original Industrial Dynamics research conducted by Forrester. Bowling and Espejo (1992) take a softer, more cybernetic approach than Towill to the study of an engineering company, concentrating on the organization of the firm.

5.7. Category 7: Business/Services

The 11 papers placed in this category reflect a wide range of industries. For the purpose of categorizing literature on the health industry, it is argued that hospitals, in an organizational sense, may be regarded as businesses as they are localized. Wolstenholme's study of community care and the health industry (Wolstenholme 1993), which was discussed earlier, falls into this category. The dynamics of a changing personnel situation in the software industry are modelled in a number of papers, e.g. a study by Levary and Lin (1991). They describe a computer tool for the management of medium to large-scale software development projects, integrated with two expert systems.

5.8. Category 8: Business/Any

The same comments apply here as to the Global/Any category, the papers placed here propose applications which are general in nature and difficult to group elsewhere. In this case, the applications relate to organizational aspects of a business. An example application has been described by Reagan-Cirincione et al. (1991). Henderson et al. (1991) used SD to investigate the operational benefits of the introduction of management information systems, with the emphasis on military applications. Dietz (1994) introduced the need for a new class of methods, based on SD concepts, for use in business redesign and re-engineering projects.

5.9. Category 9: Operations/Resources

Papers dealing with SDat an operational (detail) level are scarce, and only manufacturing operations are covered to any extent. It is unusual to break down agricultural and mineral industries into operational levels. Detailed biological models were placed in this category, e.g. that by Powers (1990), who applied control theory to the modelling of organisms.

5.10. Category 10: Operations/Manufacturing

This category, together with Business/Manufacturing, was the foundation for Forrester's Industrial Dynamics studies. He was interested in applying the concepts of feedback control systems to the detail aspects of production, e.g. inventory control, parts routing and supply chains (Wikner et al. 1991, Towill 1992, Towill and del Vecchio 1994), by considering the effects of a fluctuating demand upon the production capability of a manufacturing system. Some important work in this area, e.g. that by Towill, has been discussed in an earlier section. Only 10% of the papers surveyed were placed in this category. 5.11. Category 11: Operations/Services

Typical of the papers placed into this category are those dealing with detail levels of transport systems, e.g. Kumar and Vrat's study (1994) of the spares management policies in the Indian Railways.

5.12. Category 12: Operations/Any

No papers were found to suit this category.

6. Summary of findings

This research is based on a review of 80 research articles, from a wide variety of sources, and spans a five year period from 1990. The preceding section has described the extent to which SD is being exploited in specific areas. This section draws together this work, and observes general trends from these findings. On the basis of this review, two observations can be made about principal areas of activity and inactivity in current SD application.

Observation 1. Area of highest activity. The survey shows that the most active use of SD is for modelling resources at a global level. Indeed, resource modelling is the sector with the highest number of articles recorded. Similarly, global level is the most popular scope.

Observation 2. Area of lowest activity. Manufacturing has the lowest number of applications recorded of the three principal sectors. The lowest level of activity within this sector is modelling at a global level.

These two observations do indeed support the initial suspicion that modelling using SD within the manufacturing sector is relatively inactive. However, there are two additional observations that were quite unexpected.

Observation 3. Inconsistency of focus across sectors. Most modelling is conducted at a global level, but this is heavily biased by the resource sector. Within services, modelling is predominantly at a business level, and at an operational level within manufacturing.

Observation 4. Most articles could be directly categorized. Only 13 papers, of the 80 articles considered, could not be directly grouped as either manufacturing, resources or services.

7. Discussion

A review of this nature has two distinct limitations. First, it is reliant on research work being published in the public domain. Therefore, it ignores research conducted in private companies or government departments where dissemination is not pursued or even restricted. Second, this review only provides an indication of trends, and is an inadequate basis to fully explain them. Without doubt, many factors have combined to give the distribution of research findings shown in figure 1. Nevertheless, this review is useful as it does at least provide a structured overview of active research on the basis of the information commonly available to researchers.

On this basis, this review was initiated with a clear aim of understanding the relative exploitation of SD within manufacturing. The findings show a relative lack of exploitation, especially at higher levels of modelling. This could be explained in a number of ways, e.g. it may simply indicate that ecologists are more prolific authors than engineers. Alternatively, it may indicate a contrast between the characteristics of global modelling of resources and organizations. A third explanation could be based on the relative skill sets and exposure to modelling of ecologists relative to industrialists, and many more reasons surely exist. It is, however, possible to speculate whether this lack of exploitation is simply a missed opportunity.

The principal reasons cited above are based on a tangible distinction between the characteristics of the modelling task and the people employed in modelling. First, it is now widely accepted that SD is more suited to modelling systems at an aggregated level of detail. A global level of modelling complements these characteristics, as illustrated by the resource sector. Furthermore, SD is used at an operational level within manufacturing, and it is difficult to argue that the modelling task should become less suited to SD in this instance as the aggregated level of detail increases.

Second, engineers are generally considered to be numerate analytical people, and DES has been applied to manufacturing system modelling for over two decades. Indeed, this is probably a principal reason why eight examples of SD applications at an operational level of manufacturing are apparent in the review. Therefore, it is also difficult to argue that the skill sets of modellers can fully explain the lack of modelling at a higher level within manufacturing.

On this basis, we conclude that manufacturing system modelling does represent a missed opportunity for SD modelling, especially in the higher levels of decision making.

8. Concluding remarks

The concept of the technique of SD has been outlined, and the general changes in its main application areas have been discussed. A review of the literature has enabled analysis of the spread of applications of published SD work over recent years. A classification framework has been developed in order to study the literature in terms of industrial sector and treatment scope. Areas where research has been sparse have been highlighted and some possible reasons for neglect suggested.

To summarize the points made in the discussion, social and natural science applications have indeed proliferated over a number of years. Applications in the business field have been reasonably plentiful, with developments, e.g. management games and decision-making support systems. Manufacturing applications have been less widespread. With the continuing importance of competition through manufacturing, research into the application of SD to the modelling of manufacturing systems is encouraged. In particular, a dedicated software tool for manufacturing system modelling is lacking.

A review of this nature is able to provide guidelines for research by considering previous work in the context of a framework structure, but some criticisms can apply to this review, as discussed by Neely (1993) who conducted a production and operations management literature review. This is limited by a small sample size and the possibility of editorial and author bias. However, as Neely argues, such a review has a useful purpose if an issue can be raised. In this instance, a consideration of the literature has brought together much diverse work to be considered as a whole, and emphasized the opportunity for work on applications of SD in the manufacturing industry.

After nearly 40 years, the management science of SD may be said to be ‘mature’ in the sense that its methodology has been developed and there are several very competent general purpose computer packages available. The chief strength of the method is its versatility, and this is borne out by the broad range of situations to which it has been applied. However, the technique’s ubiquitous nature has meant that literature dealing with its applications is spread over numerous diverse publications. This paper has aimed to unite some of the different strands of SD research in order to show that the versatility of the method does not have to lead to detrimental diversification from its original purpose; a decision support technique for the manufacturing manager.

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Appendix

The 80 applications papers surveyed in this study are as follows.

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