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Invited Review

Simulation in manufacturing and business: A review

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ABSTRACT

This paper reports the results of a review of simulation applications published within peer-reviewed literature between 1997 and 2006 to provide an up-to-date picture of the role of simulation techniques within manufacturing and business. The review is characterised by three factors: wide coverage, broad scope of the simulation techniques, and a focus on real-world applications. A structured methodology was followed to narrow down the search from around 20,000 papers to 281. Results include interesting trends and patterns. For instance, although discrete event simulation is the most popular technique, it has lower stakeholder engagement than other techniques, such as system dynamics or gaming. This is highly correlated with modelling lead time and purpose. Considering application areas, modelling is mostly used in scheduling. Finally, this review shows an increasing interest in hybrid modelling as an approach to cope with complex enterprise-wide systems.

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1. Introduction and background

Since its inception, simulation has been applied to various sectors, such as manufacturing, services, defence, healthcare, and public services. It is recognised as the second most widely used technique in the field of operations management, the most popular being 'Modelling' [97,3]. Its use has been transformed by the invention and evolution of the computer, which has supported the uptake of practical simulation tools and techniques. The *suitability* or *appropriateness* and *relevance* of simulation techniques is an important factor to consider in practical real-world applications, particularly as there is a growing need to address the complexities of the whole enterprise and the difficulties of dealing with different layers of decision-making within a system. In most business environments, it is evident that changes at one level of management will have an impact on others. Clearly, there are tools that could be used at each level, but better understanding will be needed of the relationship between the different layers of organizations and of the way to connect simulation tools that relate to each layer in order to deal with the system as a whole.

So far, there have been a number of reviews in the literature on the application of simulation to manufacturing and business. Table 1 shows a list of 11 review papers published between 1999 and 2007. As it shows, a large number of papers have considered the application of simulation in supply chain management (SCM). Jansen-Vullers and Netjes [56] and Melao and Pidd [84] reviewed the application of a diverse range of simulation techniques in business process engineering. Chan and Chan [23] include a review of discrete event simulation (DES) applications in scheduling for flexible manufacturing systems (FMS). Ashworth and Carley [9] have conducted a review that addresses organisational theory and modelling using agent-based simulation (ABS) and system dynamics (SD). Shafer and Smunt [116], Smith [120], Baines and Harrison [11] target the larger domain of operations management and the application of simulation within it. However, most reviews limit themselves to either a single technique (DES or SD) or a single application area where more than one technique is used. It is worth noting, though, that Shafer and Smunt's work is the only review that considers the empirical aspect of studies. Most of the current reviews lack width of coverage, breadth of simulation techniques, and depth of application to the real-world. Hence, the purpose of this review is to fill these gaps, and review academic literature with

(1) a wider coverage of the literature;
(2) a broader scope of simulation techniques;
(3) a focus on real-world applications.

The main objective of this review is to offer a broad and extensive picture of the role of simulation techniques in manufacturing and business. It is hoped that the findings of our analysis will be beneficial to the community of simulation academics and practitioners in various sectors and industries. The first part of this paper presents a summary of the literature-review methodology developed for research, after which the results of the literature search are presented together with some trend analysis and discussion of the results. Finally we present concluding remarks and further research in the simulation field.

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Table 1
Review papers reporting the literature on simulation applications in manufacturing and business.

Review authors	Year of publication	Application	Simulation techniques or tools	No. of papers included
Van Der Zee and Van Der Vorst	2005	SCM	(1) General-purpose simulation languages (2) ABS (3) Visual interactive simulation	26
Chan and Chan	2005	SCM	ABS	14
Terzi and Cavalieri	2004	SCM	(1) Parallel simulation (2) Distributed simulation	80
Kleijnen and Smits	2003	SCM	(1) Spreadsheet simulation (2) DES (3) SD (4) Business games	22
Jansen-Vullers and Netjes	2006	Business process engineering	(1) Petri-nets (2) DES	37
Melao and Pidd	2003	Business process engineering	(1) General-purpose simulators (2) Microsoft applications (3) Simulators originally designed for manufacturing (4) System dynamics (5) Analytical models (6) Monte Carlo simulation (7) Bespoke programming (8) Process mapping (9) Special-purpose business process simulators	82 Questionnaire responses
Chan and Chan	2004	FMS scheduling (inc. 5 sub-categories)	DES	50
Ashworth and Carley	2007	Organizational theory and modelling	(1) ABS (2) SD	28
Shafer and Smunt	2004	Operations management (including 17 categories)	Not examined	85
Smith	2003	Manufacturing system design and operation (each including 4 sub-categories)	DES	172
Baines and Harrison	1999	Operations management in various industries at 3 levels; global, business and operation	SD	80

2. Literature-review methodology

Our review reports on the academic publications about simulation applications in manufacturing and business over the 10 years from 1997 to 2006. It includes all the simulation techniques encountered in the literature and follows an extensive, systematic search within the academic peer-reviewed literature. The review also contains both empirical and non-empirical studies focusing mainly on the former group. It reviews past research into process and management rather than into engineering, technical and physical design, where simulation has also made a dramatic impact. Given such breadth and width, it was important to establish an efficient method to process this amount of literature while, at the same time, capturing the important elements of the overall picture. The following subsection presents the building blocks of the search methodology employed.

2.1. Methodology design

A literature-review of the use of simulation was carried out, comprising two stages as depicted in Fig. 1 [34]. The Scopus citation database (http://www.scopus.com) was searched to identify the papers. Scopus is arguably the largest citation database indexing approximately 15,000 peer-reviewed journals from more than 4000 publishers [35]. It also includes all but two of the 38 journals listed in the review papers by Theoharakis et al. [129], Olson [93] and Barman et al. [12], which examine the most relevant and the highest quality journals in the field of operations management.

The visualisation tool 'CiteSpace' [26] was applied for several purposes during our study, for instance to exclude some irrelevant papers – such as 'Simulation for Physical Design'. As an example, Fig. 2 illustrates one snapshot of the CiteSpace results that demonstrates clusters of papers, which are formed by papers sharing the same keyword. The size of the cluster is proportional to the number of papers that use the particular keyword representing the

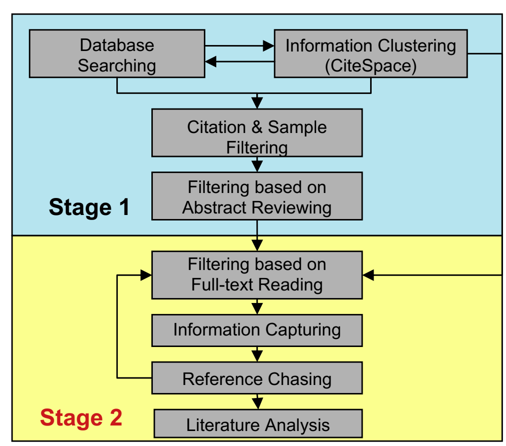

Fig. 1. The literature-review framework.

cluster. As a result, the literature was visually organised based on the authors' keywords enabling us to distinguish between the relevant and irrelevant groups of academic papers. For instance, we were able to identify some irrelevant clusters of papers concerning methods such as *finite element method* (fem), *finite element analysis* (fea), *rapid prototyping*, and *hydro-forming*; 'Physical Design' constitutes the main theme of these papers.

A hybrid sampling mechanism using two criteria, namely citation-count and random sampling, narrowed down the search further. The hybrid mechanism was applied to the batches of papers published in each individual year from 1997 to 2006 and equal numbers of citation-selected and randomly selected papers were used for each year. The citation-count criterion provided more high quality papers, while the random selection enabled us to include some of the recently published papers with low citations. Reading the abstracts was the next step of the process in order to sift out the irrelevant papers by employing academic judgment.

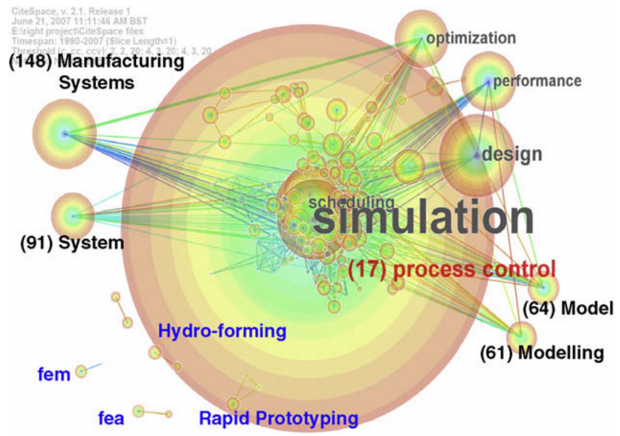

Fig. 2. A snapshot of CiteSpace results.

The abstract-selected subset of papers was then subjected to full-text reading during which information capturing, final screening, and classification of the papers were carried out. Information captured and extracted from full-text reading was fed into a template form for further use and analysis. Reference chasing was also performed whilst reading the full-text, and the relevant references were added to the list of papers to be analysed [43].

2.2. Classification schemes

In order to analyse and interpret the results in a more standardised way, the papers were classified in terms of two attributes: the empirical nature of the papers and the simulation application used. To analyse the empirical nature of the papers, we classified the literature into three groups, defined as follows:

- *Class A or Real Problem-Solving papers*: simulation has been applied on a real problem with real data. This class demonstrates a project with a significant level of user engagement in the simulation part.
- *Class B or Hypothetical Problem-Solving papers*: simulation has been applied for the purpose of solving a real-life problem, but using artificial data rather than real data. This is usually aimed at providing generic solutions.
- *Class C or Methodological papers*: research is conducted to enhance the methodology of simulation itself regardless of any specific application area without experimental study. This class and class B do not usually involve real stakeholders.

We follow a similar definition used by Shafer and Smunt [116] for empirical studies: "if either empirical data was used as a basis for setting the level of key parameters in the simulation study or the simulation study itself was directly motivated by a problem identified empirically". Our study, however, makes a further distinction between real data and artificial data as represented by

Table 2
Categorization of simulation applications (an adaptation of [116]).

Category code	Application	Sub-categories
(AssyLB)	Assembly line balancing	Design and balancing of assembly lines
CapP	Capacity planning	Uncertainty associated with capacity planning, changing capacity levels (e.g., adding handling/storage resources, effects of bed reductions at a hospital, number of berths at a port), sequencing the expansion of current resources, improving current operations to increase capacity
CellM	Cellular manufacturing	Comparing planning and control systems in CM environments, comparing scheduling rules in cellular versus functional layouts, comparing alternative cell formation techniques, cell design
Trans	Transportation management	Delivery of finished goods from distribution centres or plants, vehicle routing, logistics management, truck dispatching, truck loading, vehicle and air traffic management, incident management, travelling salesman problem, travel congestion pricing
FACLOC	Facility location	Locating facilities to minimize costs
Fore	Forecasting	Comparing performance of alternative forecasting models
InvMgt	Inventory management	Risk and cost of holding inventory, determining inventory levels, continuous replenishment, inventory policy, determining reorder points and batch sizes
JIT	Just-in-time	Design of Kanban systems, how Kanban can be used
PrcEMan	Process engineering-manufacturing	Process design and improvement, Anticipating start-up problems, investigating equipment and operating problems in planning stage, design of new facility, performance measurement
PrcESer	Process engineering-service	Design, evaluation, and implementation of new technologies; multiple changes to service delivery process including scheduling rules, capacity, layout, analysis of bottlenecks, performance measurement
PPic	Production planning and inventory control	Two or more of the following topics: safety stock, batch size, bottlenecks, Rop methods, forecasting, and scheduling rules
Purch	Purchasing	Economics of minimum purchase quantities, heuristics for purchase batch sizes
RsrcAll	Resource allocation	Allocating equipment to alternate locations/jobs overtime to stations to improve process flows, raw materials to plants, empty containers to vessels, organs to patients, resource selection
Sched	Scheduling	Throughput times, delivery reliability, job sequencing, development of equipment schedules, production scheduling, scheduling resources to minimize idle time, matching labour to demand, order release, flight scheduling, shop-floor control
Stgy	Strategy	Illustrate planning methodology, strategic planning, functional strategies, public policy making, industry policy making
SCM	Supply chain management	Instability in supply chain, multi-echelon inventory/distribution systems, amplification Phenomenon
WrkfcP	Workforce planning	Workforce scheduling, cross-training, labour staffing versus customer service levels, labour flexibility versus investing in equipment
Maint	Maintenance management	
KM	Knowledge management	Knowledge creation, innovation, organizational learning, learning curve, new product development, technology management, knowledge transfer
PM	Project management	Project planning and control, multi-project management
OD	Organizational design	Organizational structure, organizational behaviour, customer behaviour analysis, team working, organizational culture, change management, business ethics
MgtTr	Management training and education	Teaching management courses
FM	Financial management	Cost estimating, cost accounting, portfolio management, risk assessment
QM	Quality management	Quality of service, customer satisfaction, quality assurance and quality control, supplier quality, continuous improvement, six sigma, total quality management, lean approach, benchmarking

Table 3
List of 20 journals with the highest number of papers in the current review.

Journal title	Journal title
Computers and Industrial Engineering	Int. J. of Project Management
Decision Sciences	J. of Operational Research Society
Decision Support Systems	J. of Manufacturing Technology Management
Euro. J. of Operational Research	J. of Systems and Software
Interfaces	Management Science
Int. J. of Advanced Manufacturing Technology	Production and Operations Management
Int. J. of Computer Integrated Manufacturing	Production Planning and Control
Int. J. of Operations and Production Management	Simulation
Int. J. of Production Economics	Simulation and Gaming
Int. J. of Production Research	Transportation Research

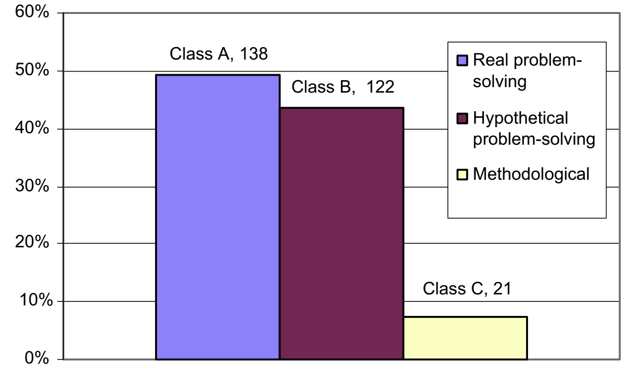

Fig. 3. The number of simulation studies by their empirical nature.

class A and B. Furthermore, our review captures some information from non-empirical studies represented here as class C.

The papers were also classified into 24 categories based on the simulation applications, as listed in Table 2. The first 17 categories are mainly extracted from Shafer and Smunt [116], whilst the last 7 categories have been added based on the findings of the present review. Moreover, a more general category 'Transportation Management' has replaced the 'Distribution' category in Shafer and Smunt's scheme. Other minor amendments to the Shafer and Smunt's scheme are indicated in italic font.

2.3. Methodology implementation

The literature search was conducted using the Boolean keyword combination "(simulat* OR 'system dynamics') AND (manufacturing OR business OR management)". Although 'System Dynamics' is a kind of continuous simulation technique, it does not include 'Simulation' as a word and for this reason it was added to the search string. The process generated around 20,000 papers at the outset, which were narrowed down to around 4600 papers using the Scopus searching tools such as 'Limit to', as well as the CiteSpace tool.

Sampling returned around 1200 papers. Further filtering, based firstly on abstract reviewing and secondly on full-text reading, resulted in a set of 257 relevant papers. Reference chasing and other access methods such as personal contacts added 24 more papers to the list, making it a total of 281 papers published in 108 journals and 5 conference proceedings. A list of 20 journals with the highest number of papers in our review is shown in alphabetical order in Table 3.

3. Results

Fig. 3 presents the percentage and number of papers in this review, in the classes A, B, and C, based on their empirical nature. It can be seen that simulation has been used to solve a problem (whether a real-life problem or a hypothetical one) in over 92% of the studies (class A + class B), whereas the remaining 8% have explored theoretical issues without conducting simulation experiments.

Table 4 presents the main result of this review, showing various applications of simulation techniques in a range of industry sectors. For brevity, only a sample of Class A references is shown in the table (typically one paper per row). The last two columns show the total number of Class A papers and total number of papers irrespective of class.

Fig. 4 shows the number of simulation studies by application category. 'Scheduling' is the application area with most references, which agrees with findings reported in Shafer and Smunt [116]. 'Process Engineering in Manufacturing', which includes both process design and improvement, accounts for the second most popular application of simulation, while other applications including 'supply chain management (SCM)', 'Strategy', 'Transportation', and 'Project Management' come further down in the list. There is a surprising surge in strategy modelling (Stgy). However, this is mainly attributed to the rising use and utilisation of system dynamics. In addition, we found a noticeable number of papers on project management (PM), management training, knowledge management (KM) and organisational design (OD), none of which was reported in Shafer and Smunt [116].

Table 5 shows how the overall patterns of some of the simulation applications have varied over the past 10 years. SCM maintains a visibly increasing trend, mainly because simulation is regarded as the main technique for supporting decision-making on supply chain design, owing to its inherent modelling flexibility [132]. This finding is highly consistent with the number of review papers on SCM, as noted in Section 1. A fair growth in the organisational design (OD) area demonstrates a rising interest of the simulation community in the abilities of simulation to address organizational topics. 'Production Planning and Inventory Control', which represents the mix of applications around planning and control, also shows a growth that could be explained by the recent practices in hybrid simulation (where two or more simulation techniques are linked together and used simultaneously to solve the problem). In contrast, a falling trend with respect to the 'Process Engineering in Manufacturing' seems evident.

In terms of techniques, results show that discrete event simulation (DES) has been used in over 40% of the papers reviewed and is therefore the most widely used technique in manufacturing and business (see Fig. 5). It has been applied in a variety of industries for a wide scope of operational management applications including scheduling, production planning and inventory control, process engineering, and inventory management, SCM and project management purposes. This implies that DES has been appropriate for tactical and operational decision-making levels. Also, DES tends to be convenient for detailed process analyses, resource utilisation, queuing, and relatively shorter-term analyses. This finding confirms the earlier research carried out by Kellner et al. [59].

Based on our review, system dynamics (SD) is the second most widely applied simulation technique in manufacturing and business, with a popularity rate of over 15%. Its use has been focused on such domains as policy and strategy development, project management, SCM, as well as knowledge management. Table 4 implies that SD's application areas are strategic decision-making level and analyses, high level perspectives, as well as qualitative analysis (e.g. knowledge management). Clark and Jones [29] present a recent example of SD's application in knowledge management where the authors look into the assessment of a theoretical model of

Table 4
Applications of simulation techniques in manufacturing and business.

Application	Simulation technique	Industry sector	A sample of Class A papers	No. of Class A papers	Total no. of papers (Class A + B + C)
Assembly line balancing	DES	Computer hardware	[85]	1	1
	Other hybrid techniques	Optic lens assembly	[142]	1	1
Capacity planning	DES	Generic service industries	–	–	1
		Generic part manufacturing	–	–	5
		Pump production	–	–	1
		Transformer manufacturing	[61]	2	2
		Beverages	[136]	1	1
	SD	Extruded food production	[96]	1	1
	Monte Carlo simulation	Electricity generation	–	–	1
	Petri-net simulation	Generic part manufacturing	–	–	1
	Other hybrid techniques	Financial/insurance and education	–	–	1
Cellular manufacturing	Virtual simulation	Automotive	[94]	1	1
Transportation management	DES	Urban traffic management	[111]	1	1
		Stationary production	[90]	1	1
		Concrete transport	–	–	1
	ABS	Railway transport	[16]	1	1
		General transport	–	–	1
	Petri-net simulation	Generic part manufacturing	–	–	1
	Traffic simulation	Traffic control, freeway traffic control	[17]	9	9
		City logistics	–	–	1
	Hybrid (SD&DES)	Traffic control	–	–	1
	Other hybrid techniques	Highway traffic control, urban traffic control	[66]	4	5
	Other techniques	Airport management	[130]	1	1
		Travel navigation	[62]	1	1
Facility location	Other hybrid techniques	Transportation	[63]	1	1
Forecasting	SD	Aircraft manufacturing	[75]	1	1
Inventory management	DES	Generic part manufacturing		–	3
		Automotive	[110]	2	2
		Construction	[101]	1	1
		Chemical products	[83]	1	1
		Recycled parts	–	–	1
		Insurance and education	[32]	1	1
	Monte Carlo simulation	Nuclear and spacecraft	–	–	1
	Other techniques	Retailing	–	–	1
Just-in-time	DES	Generic part manufacturing	–	–	3
	Intelligent simulation	Generic part manufacturing	–	–	1
Process engineering-manufacturing	DES	Ship building	[98]	1	1
		Automotive	[100]	3	3
		Pharmaceuticals	[15]	1	1
		Generic part manufacturing	[33]	2	7
		Electronics	[109]	3	4
		Aluminium gas cylinder	[42]	1	1
	SD	Automotive	[25]	1	1
		Generic part manufacturing	–	–	1
	ABS	Generic part manufacturing	[69]	1	1
	Monte Carlo simulation	Generic part manufacturing	–	–	1
	Petri-nets simulation	Generic part manufacturing	–	–	1
	Virtual simulation	Generic part manufacturing	–	–	1
		Electronics	[22]	1	1
	Intelligent simulation	Generic part manufacturing	–	–	2
		Electronics	–	–	1
	Other hybrid techniques	Generic process industry	–	–	1
	Other techniques	Various manufacturing industries	[38]	1	1
		Beverage	–	–	1
Process engineering-service	DES	Retailing	–	–	1
		Generic service industry	–	–	1
		Printing	[40]	1	1
		Consulting	[52]	1	1
		Distribution	[71]	1	1
		Container terminal	[114]	1	1
		Construction waste handling	[27]	1	1
		Construction	–	–	1
	SD	Logistics	[8]	1	1
		Insurance	[1]	1	1
	Distributed simulation	Electricity generation	[73]	1	1
		Information and communications	[119]	1	1

(*continued on next page*)

Table 4 (*continued*)

Application	Simulation technique	Industry sector	A sample of Class A papers	No. of Class A papers	Total no. of papers (Class A + B + C)
Production planning and inventory control	DES	Electronics	[57]	1	1
		Generic part manufacturing	–	–	3
	ABS	Generic part manufacturing	–	–	1
	Distributed simulation	Aluminium production	[143]	1	1
		Heater manufacturing	[58]	1	1
		Automotive	[106]	1	1
	Hybrid approach (DES&SD)	Generic part manufacturing	–	–	2
		Electronics	[104]	1	1
	Other hybrid techniques	Aluminium sheet production	[6]	1	1
Purchasing	DES	Energy	–	–	1
Resource allocation	DES	Transportation	[46]	1	1
		Generic manufacturing	–	–	1
	ABS	Shipping terminals	[39]	1	1
	Monte Carlo simulation	Jet engine repair	–	–	1
	Distributed simulation	Electricity	–	–	1
	Intelligent simulation	Generic manufacturing	–	–	2
	Hybrid approach (DES&SD)	Semi-conductor manufacturing	[105]	1	1
	Other hybrid techniques	Research	[77]	1	1
	Other techniques	Construction	–	–	1
Scheduling	DES	Generic part manufacturing	[121]	1	14
		Semi-conductor manufacturing and electronics	[14]	4	5
		Container terminals	[44]	1	2
		Airline	[138]	1	1
		Re-manufacturing	–	–	1
		Printing	[87]	1	1
	ABS	Generic part manufacturing	–	–	1
	Monte Carlo simulation	Electronics	–	–	1
	Petri-nets simulation	Generic part manufacturing	–	–	1
	Intelligent simulation	Generic part manufacturing	–	–	4
		Computer hardware	[31]	1	1
	Other hybrid techniques	Generic part manufacturing	–	–	1
	Other techniques	Generic part manufacturing	–	–	1
Strategy	DES	Furniture manufacturing	[18]	1	1
	SD	Electronics	[123]	1	1
		Generic part manufacturing	–	–	1
		Consulting	[76]	1	1
		Automotive	[55]	1	2
		Electricity generation	[135]	1	1
		Financial and aircraft manufacturing	[74]	1	1
		Information and communication	[140]	2	2
		News publication	–	–	1
		High-tech	[80]	1	1
		Chain restaurant	[65]	1	1
		Aeroengine manufacturing	[103]	1	1
		National energy management	[88]	1	1
		Construction	[68]	2	3
	ABS	Information and communication	[28]	1	1
		Electricity	[95]	1	1
		Generic part manufacturing	–	–	2
	Simulation gaming	Financial and insurance	[49]	1	1
	Monte Carlo simulation	Generic part manufacturing	–	–	1
		Energy	–	–	1
	Hybrid (SD&DES)	Electronics	[13]	1	1
	Other techniques	Information and communications	–	–	1
Supply chain management	DES	Generic part manufacturing	[20]	3	7
		Chemical products	–	–	1
		Food	[21]	1	1
		Notebook computer	[117]	1	1
		Retailing	[36]	1	1
	SD	Electronics		–	1
		Generic part manufacturing	–	–	2
		Machine tools manufacturing	[4]	1	1
	ABS	Mold manufacturing	–	–	1
		Appliance/electronics/computer	–	–	1
		Computer hardware	[126]	1	1
	Simulation gaming	Chemicals	[133]	1	1
	Petri-nets	Food	[131]	1	1
	Distributed simulation	Automotive	[127]	1	1
		Generic part manufacturing	–	–	1
	Hybrid approach (DES&SD)	Information and communication	[107]	1	1

Table 4 (*continued*)

Application	Simulation technique	Industry sector	A sample of Class A papers	No. of Class A papers	Total no. of papers (Class A + B + C)
		Generic part manufacturing	–	–	1
	Other hybrid techniques	Trading	[7]	1	1
		Generic part manufacturing	–	–	2
		Packaging/machine manufacturing/iron metallurgy/apparel manufacturing/dairy	[79]	1	1
Workforce planning	DES	Franchised food	[50]	1	1
		Electronics	[115]	1	1
		Airplane manufacturing	[145]	1	1
		Call centres	–	–	1
	Other hybrid techniques	Steel production	[86]	1	1
Maintenance management	DES	Generic part manufacturing	–	–	1
	Monte Carlo simulation	Generic part manufacturing	–	–	1
	Virtual simulation	Machine building	–	–	1
Knowledge management	DES	Generic part manufacturing	[10]	1	1
		Aircraft manufacturing	–	–	1
		Construction	–	–	1
	SD	Generic part manufacturing	–	–	2
		Pharmaceutical	[137]	1	1
Project management	DES	Aircraft maintenance	–	–	1
		Oil and gas	[19]	1	1
		Chocolate	–	–	1
		Construction	–	–	1
		Software development	[5]	1	1
		Consulting	–	–	1
	SD	Semi-conductor manufacturing	[37]	1	1
		Software development	[108]	2	6
		Generic projects	–	–	1
		Construction	[72]	1	1
	Monte Carlo simulation	Software development	–	–	1
		Construction	–	–	1
	Petri-net simulation	Construction	[112]	1	1
	Intelligent simulation	Construction	–	–	1
	Hybrid approach (DES&SD)	Software development	[81]	1	2
Organizational design	DES	Generic part manufacturing	–	–	1
	SD	Pharmaceutical	[113]	1	1
	ABS	Generic part manufacturing	–	–	3
	Simulation gaming	Information and communications	[92]	1	1
	Other hybrid techniques	Generic manufacturing	–	–	1
	Other techniques	Trading	[41]	1	1
		Pharmaceuticals	[51]	1	1
Management training and education	DES	Education	[139]	1	1
	SD	Education/software development	[99]	1	1
	Simulation gaming	Education	[144]	2	3
		Construction	[91]	1	1
		Clinical instrument manufacturing	[64]	1	1
	Distributed simulation	Education	–	–	1
	Virtual simulation	Education/construction	–	–	1
	Other hybrid techniques	Education	[78]	1	1
	Other techniques	Education	[47]	1	2
		Construction	–	–	1
Financial management	DES	Electronics	[122]	1	1
		New-product-development	–	–	1
	Monte Carlo simulation	Stock markets	[141]	1	1
		Property	[48]	1	1
		Accountancy	–	–	1
Quality management	DES	Software development/education	–	–	1
		Automotive	[30]	1	1
	SD	Computer hardware	[124]	1	1
		Construction	[67]	1	1

management support systems, while taking the user's knowledge into consideration. A wide range of industries have adopted SD, including semi-conductor manufacturing, automotive, pharmaceuticals, utility companies, as well as some service industries such as Insurance, consulting, and software development.

Apart from hybrid simulation as the next most widely technique, which will be cited later in this paper, agent-based simulation (ABS) is the fourth most popular simulation technique with a usage rate of more than 5%. One of the most common applications of ABS focuses on 'strategy' where, for example, each player of an industry is treated as an agent and every agent's strategic behaviour is modelled in relation to the classic strategy concepts [118,2], such as Porter's 5-forces model [102]. Similarly, the application of ABS in another common area – organisational development – addresses the modelling of human agents' behaviours as well as the communications inside an organisation. Another concept is the ‘autonomous agents embedded with a trust mechanism’ which models and assesses trustworthiness of the partners in a supply-chain [70].

Intelligent simulation is based on an integration of simulation and artificial intelligence (AI) techniques. The idea was put into practice perhaps for the first time in a tool called ROSS [82], which was developed by the RAND Corporation. The technique basically applies AI to tackle the volatility of real-life, or the over-complexity of some problems such as scheduling, making the solution approach quicker, sometimes real-time, as well as more manageable. An example is the work of Jahangirian and Conroy [53] in which they enable a simulation module to learn from its experiments. As Table 4 shows, scheduling has been the most common application of intelligent simulation. AI techniques, such as artificial neural networks (ANN) and genetic algorithms (GA) have also contributed significantly to the development of simulation optimization approaches.

Monte Carlo simulation (MCS) is one of the earliest simulation techniques developed, but it has played a trivial role within the manufacturing and business domains. Its usage is mainly limited to ‘static’ problems or to solve numerical problems with a stochastic nature, such as in property valuation and risk management.

Traffic simulation is a name for a group of simulation techniques specifically developed to solve traffic management problems. A relatively high number of papers using this technique prove the suitability of simulation to tackle transportation applications (see Fig. 5) and traffic problems in particular.

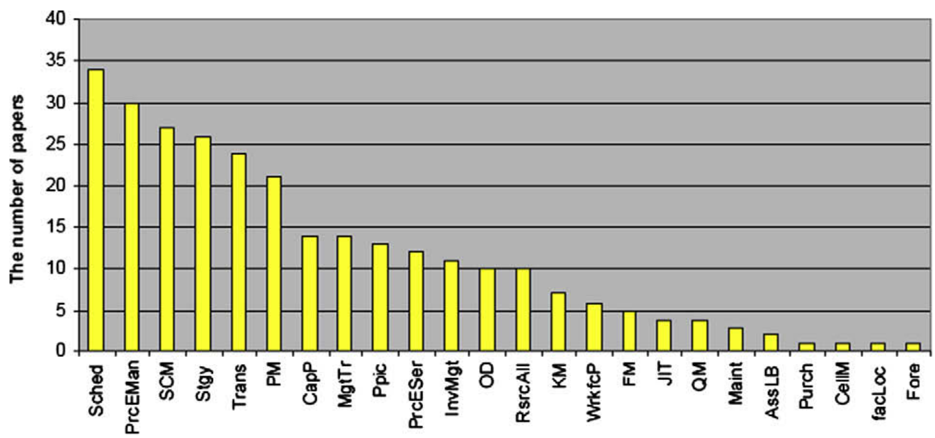

Fig. 4. Number of papers by ‘Application’.

Table 5
Number of papers for some application areas, by year.

	SCM	InvMgt	RsrcAll	CapP	PPic	OD	PrcEMan
1997	1	0	1	0	1	2	5
1998	0	4	1	0	0	0	2
1999	0	0	1	2	2	0	5
2000	2	1	0	1	0	0	6
2001	1	0	0	1	1	2	3
2002	5	0	1	3	2	1	2
2003	1	0	1	1	2	2	3
2004	4	1	0	5	1	0	4
2005	8	2	3	3	3	2	2
2006	4	5	2	0	1	3	1

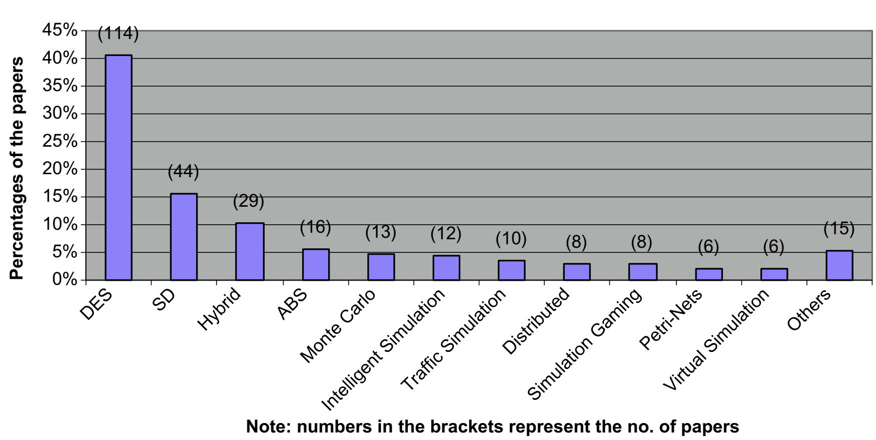

Fig. 5. Number of published papers by simulation technique used.

The main theme of *distributed simulation* is to disperse simulation functions across a network, which is in harmony with the growing trend towards decentralization schemes within organizations. This approach is basically concerned with distributed architectures, such as high level architecture (HLA), and is currently applied to organisations and problems with a network structure, such as transportation (as a part of a hybrid technique), electricity generation industry, as well as in SCM applications where network structure of the chain plays a major role. Its frequent use in military applications has also been reported in the literature [34].

Simulation gaming (SG) is another technique that is receiving special attention from the education and training sectors and has been applied in such areas as incident management training [54]. Simulation gaming has also shown its practical use where there are some pre-developed simulation games for specific industries such as insurance, financial services, or supply chains.

Petri-nets were introduced as a graphical and mathematical tool to model computer systems. Generally they can be used for describing and studying systems that are characterized as being concurrent, asynchronous, distributed, parallel, and stochastic. Petri-nets support all the features needed to model processes. However, our review did not find any particular pattern of use for this technique, as it has been encountered in a wide variety of applications and industries (see [45] for a study of Petri-net based modelling and simulation techniques in the context of manufacturing, workflows and transportation systems).

Virtual simulation offers companies the ability to model and simulate a system in a three-dimensional, immersive environment. It usually forms part of a broader effort to develop virtual environments (e.g. virtual factories) that managers and engineers use to have a more clear, and more reliable picture of any change's impacts on the system. The data in such an environment will be shared for analyses in various activities including product development, production planning, assembly analysis, work study, workplace design, operation simulation and plant layout [22]. Our review appears to show some similarity patterns relating the application of virtual simulation to the areas of process engineering and production planning.

In addition to the studies applying stand-alone simulation - techniques, the present review identified 29 papers using *hybrid simulation*, listed third place with over 10% popularity. These studies bring together various simulation techniques to solve a problem. The best known example of such an approach is the combination of DES and SD, which was found in 11 papers reviewed. The research on this particular combination has focused on the concept of 'Enterprise Modelling and Simulation' where the impact of production decisions, evaluated using DES models, is investigated on enterprise level performance measures. The SD simulation captures long-term effects of these decisions, in a holistic sense that are appropriate for higher management levels, while DES provides detailed analyses of the shorter-term decisions and actions [105]. Another example of such integration is a hierarchical production planning architecture consisting of SD components for the enterprise level planning, and DES components for the shop-level scheduling [134]. We believe that this integration approach will hold promise during the next decade.

4. Discussion

Our review reports a remarkable increase of the percentage of empirical research (class A + class B) in simulation studies published over the past 10 years (92%), compared to the findings reported in Shafer and Smunt [116] as being only 14% for the whole period of 1970–2000. This may be attributed to the accumulated knowledge and experience in the industries, as well as the availability of tools and awareness of benefits. Moreover, the high level of competition in the market over recent years might have contributed to an increasing use of simulation techniques in practice.

Table 6
Number of papers for 5 simulation techniques, by year.

	DES	SD	ABS	Gaming	Hybrid (DES&SD)
1997	11	4	1	0	0
1998	13	4	1	0	0
1999	14	3	0	0	0
2000	7	3	3	0	2
2001	8	5	2	0	2
2002	10	3	2	2	1
2003	6	7	1	2	1
2004	14	5	1	0	1
2005	18	7	3	0	4
2006	18	6	3	4	0

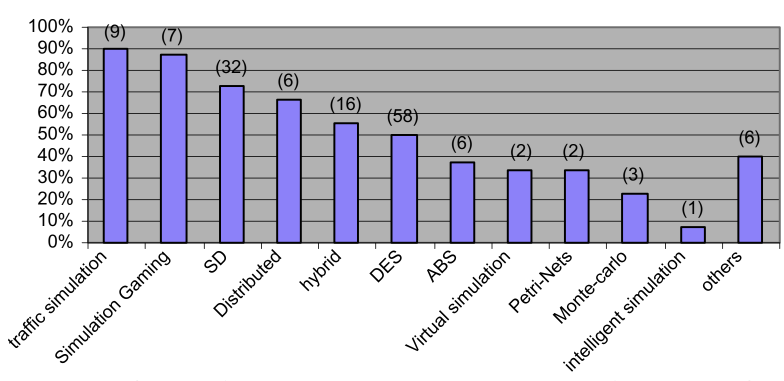

Fig. 6. The percentage of real problem-solving papers (class A) for each simulation method.

The results also suggest that in addition to some classic applications such as scheduling and process engineering, simulation techniques are also being found very useful for a variety of other application areas such as strategy, supply chain management, knowledge management, project management training and organizational design. This observation confirms the deduction made in Shafer and Smunt's study, therefore claiming a clear pattern of application diversity to sustain in the future.

When examining historical trends in the use of various simulation techniques over the past 10 years, five techniques – namely DES, SD, ABS, simulation gaming (SG) and hybrid (SD and DES) – showed a fairly high growth, shown in Table 6. Although DES experienced a drop in usage between 2000 and 2003, this trend was later reversed, making DES the most popular simulation technique. This finding could be associated with a continuous growth in the DES software tool market (see [125]), yet it requires more investigation (see [89,11] for a historical analysis of DES and SD, respectively). The growing trend in the other 4 simulation techniques could be justified by the assumption that the emerging benefits of these techniques are becoming more evident in practice.

In order to see if there is any correlation between a simulation technique and the level of stakeholder engagement, we compared the percentage of real problem-solving papers (class A) for each simulation technique. Interestingly, as it can be seen in Fig. 6, "traffic simulation" and "simulation gaming" account for the highest stakeholder engagement rates among the range of simulation techniques, with 9 out of 10 papers and 7 out of 8 papers using real data, respectively. It should however be noted that the number of papers is too small to reflect the real situation for these techniques. Traffic simulation benefits from the nature of the traffic-control problem, for which it is perhaps easier to gather data and carries more relevance to society and everyday life. Simulation gaming has been mainly used in educational environments with the learners as the stakeholders willing to get involved in the interactive, game-like tools and techniques. SD, distributed simulation and hybrid simulation also show an impressively high stakeholder-engagement rate. This high rate of stakeholders-engagement might be due to SD's capability to accommodate qualitative descriptions rather than detailed quantitative elements that require prolonged data collection activities. It also enables stakeholders to gain holistic and strategic perspectives about the system. Although DES is the technique with the highest number of real problem-solving papers, the difficulty with detailed data gathering that it takes long time to complete the exercise which reduces stakeholders continued interest. More specifically, this review claims that only half of the studies using DES have used real data. A significantly low implementation rate with regard to Intelligent Simulation can be explained by the fact that research in this area is still in its infancy.

5. Conclusions and future research

Over 60 years of simulation presence in the areas of manufacturing and business, has led to a wide spectrum of successful applications in different areas such as design, planning and control, strategy making, resource allocation, training, etc. This review reports on publications concerning simulation applications in manufacturing and business over the 10-year period 1997–2006. Although this review has not covered the whole population of relevant publications, we believe it is distinguished from previous attempts from three perspectives: wider coverage of the literature sources, broader scope of the simulation techniques, and a focus on real-world applications. The review was implemented in two stages in which the search process was narrowed down systematically from around 20,000 to 281 papers. There are a number of specific issues that can be concluded from this review:

- This review shows that DES – despite its popularity – does not possess the same level of stakeholder engagement as, for example, traffic simulation and simulation gaming do. This is possibly attributed to the difficulty and time needed for data gathering, which usually repels stakeholders in the fast pace of today's business.
- On the other hand, we find that SD scores higher in terms of stakeholder engagement, because it uses standardised conceptual modelling techniques that enrich brainstorming. This is in addition to its lesser reliance on hard data when compared with DES. Simulation gaming is also found to have a higher level of user engagement, because it is mostly utilised for education and training.
- Applicationwise, scheduling scores the highest as an application area for modelling. This is mainly attributed to the fact that this area is well defined with known variables. The difficulty usually is in finding a reliable analytical method. This is not usually the case for systemic problems where the need for modelling is vague and the outcomes are not tangible enough to be recognised. We also find that there is growth in strategic modelling, which is enhanced by the increased usage of SD.
- Our review adds new application areas to those of Shafer and Smunt [116]: project management (PM), management training, knowledge management (KM) and organisational design (OD). This is an interesting finding because it reflects the rising appreciation of organisations of softer aspects of their performance enhancers.
- Another interesting finding is the rising profile of hybrid modelling (where two or more techniques are used simultaneously). In fact it is the third most widely reported approach. We believe this is largely fuelled by the current trends to provide enterprise-wide solutions and the common belief that different parts of an organisation – however different in structure – will have mutual impacts. The use of this approach is likely to grow in the next few years, given the pace of technological advancement.

Generally speaking, this review asserts that during the recent decade the simulation literature has witnessed a major *diversification* phenomenon both in terms of OR techniques and applications. This will open doors to new opportunities and challenges. Another major trend observed is an evidenced move towards *empirical* studies compared to methodological ones. This demonstrates a clear sign of maturity in the discipline. More investigations and analyses of real problem-solving papers (class A), challenges, lessons learned, and new findings with a focus on the stakeholders engagement issue will establish a promising line of further research. Another interesting avenue for future research is a comparative historical and evolutionary analysis of various simulation techniques with a larger sample of papers, which would extend the current review to include grey literature. Furthermore, studies of simulation success and failure stories would help simulation researchers and practitioners to conduct more efficient and successful works both in developing new techniques and applying the present techniques in new domains.

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