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A survey of the application of fuzzy set theory in production and operations management: 1998–2009

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ABSTRACT

The objectives of this research are to identify the research trends in and publication outlets for the applications of the fuzzy set theory technique in production and operations management (POM). The major findings indicate that (1) the most popular applications are capacity planning, scheduling, inventory control, and product design, (2) some application areas make more use of particular types of fuzzy techniques, (3) the percentage of applications that address semi/unstructured types of POM problems is increasing, (4) the most common technologies integrated with the fuzzy set theory technique are genetic/evolutionary algorithms and neural networks, and (5) the most popular development tool is C Language and its extension. Our survey confirms several research trends, some of which are unexpected and some of which contradict previous findings.

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1. Introduction

In the 1960s, Professor Lotfi Zadeh created fuzzy set theory to mathematically represent uncertainty and vagueness. This theory reflects human reasoning in its use of approximate information and uncertainty to generate decisions. It has further been used to develop formalized tools to deal with the imprecision intrinsic to a wide variety of problems. Over the past four decades, fuzzy set theory has gained in popularity, and there are now more than 2000 commercially available products that make use of it, ranging from washing machines to high-speed trains. Nearly every application is potentially able to realize some of the benefits of fuzzy set theory, including better performance, higher productivity, better efficiency, and lower cost.

In academia, most of the early fuzzy set theory research focused exclusively on scientific applications. It was not until the late 1980s that this state-of-the-art technique was used to develop a wide variety of business applications and that, as a result, an increase in amount of published research began to appear. In particular, research into the application of fuzzy set theory in the area of production and operations management (POM) has been very successful and thus remains prolific.

Three reviews of the use of fuzzy logic in POM applications have been published in the literature. Du and Wolfe (1997) explored the use of fuzzy logic and neural networks in industry, particularly in the areas of scheduling and planning, inventory control, quality control, group technology, and forecasting, and suggested four types of integration between the two to-stimulate future research. Proudlove et al. (1998) carried out a review of the use of various artificial intelligence (AI) techniques as solutions to eight areas of POM, although fuzzy logic was briefly discussed in only two of these application areas, namely, product design and scheduling. The most recent review was a survey of AI and operational research (OR) in POM conducted by Kobbacy et al. (2007). Their study examined four AI techniques, namely, genetic algorithms (GAs), case-based reasoning, knowledge-based systems, fuzzy logic, and hybrid systems. They then discussed the application of each technique in four areas of operations management, including design, scheduling, process planning and control and quality, maintenance, and fault diagnosis. These reviews presented an overall view of the use of AI techniques in certain POM applications, but did emphasize fuzzy logic techniques and covered only a few POM areas. In addition, two of the reviews are somewhat out-of-date, as they were conducted about 12 years ago. Furthermore, none of them surveyed the historical trends in fuzzy set theory applications or analyzed and identified the potential journal publication channels for related research.

Our study has two objectives. The first objective is to examine the historical trends in published fuzzy set theory research into POM applications, and particularly the trends related to application areas, methods, decision types, AI technology integration, and development tools. The second is to identify the best publication outlets for such research, because although there are many reputable POM journals worldwide, some may not publish work on AI applications. We also consider it worthwhile to determine

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whether some journals prefer to publish articles on certain types of POM applications.

By definition, fuzzy set theory encompasses fuzzy logic, fuzzy arithmetic, fuzzy mathematical programming, fuzzy topology, fuzzy graph theory, and fuzzy data analysis. As our surveyed applications cover all of these techniques, the collective term "fuzzy set theory" is used throughout this article, although "fuzzy logic" alone is often used in the literature.

The remainder of this paper begins in Section 2 presenting the data collection method that we adopted to gather information on the published fuzzy set theory applications in the POM literature, including a list of the journals surveyed. Section 3 discusses our classification scheme and the approach used to classify and organize the identified applications. Section 4 provides the results of these classifications, including the historical trends in the main classification categories. A discussion of our findings is presented in Section 5. Section 6 sets out the limitations of the study and makes suggestions for future work. A summary and conclusions are presented in Section 7.

2. Data collection method

Chaudhry and Luo (2005) conducted a study of the applications of GAs in POM, identifying 21 journals for review. Their selection was based on a comparison of three studies of journal rankings and categorizations (i.e., Goh et al., 1997; Soteriou et al., 1999; Barman et al., 2001), from which they elected to adopt the journal list in Barman et al. (2001), as the findings of that study were deemed to be the most comprehensive and representative one. As this list consists of internationally recognized leading POM and business journals, we thus adopt it here.

The most important step in our literature retrieval process was a computer search of the ABI/INFORM and Business Source Premier databases. Our search period covered the 12 years from January 1998 to December 2009. Using the descriptor "fuzzy" and the title of each journal, we retrieved approximately 800 abstracts for review from the specified period. A manual search was then conducted for four journals, *Naval Research Logistics*, *Operations Research*, *Production and Inventory Management*, and *Production and Operations Management*, as these journals or certain issues of them were found to be unavailable in the databases.

Each article retrieved through this process was carefully reviewed before a decision was made on its inclusion in the survey. We required that each article discusses the prototype or development of a fuzzy set theory application for POM. This requirement eliminated many of the articles retrieved from the databases, as the descriptor that we used produced abstracts from numerous articles that did not necessarily describe POM applications.

3. Classification categories

A final total of 402 articles, or 403 applications, were considered to be acceptable for the purposes of this study. As each article was reviewed, it was classified according to the following categories:

(1) Year of publication
(2) Country/institution affiliation of the author(s)
(3) Journal
(4) Application area
(5) Method
(6) Decision type
(7) AI technology integration
(8) Development tool

The classification of most of the categories was quite simple and straightforward, with the exception of application area and decision type. We adopted the approach of Chaudhry and Luo (2005) for the classification of these two categories, which combines the work of Jayaraman and Srivastava (1996) and Keen and Morton (1978), as it was considered to be most appropriate for our review. Readers are referred to their articles for a thorough discussion and justification of the approach. Table 1 presents the application areas and the associated decision types.

Although most of the classifications of application area were reasonably clear, some inevitably required subjective judgment. To ensure accuracy, each of the authors performed the classifications independently, and then compared their results. Any discrepancies were thoroughly discussed until a consensus was reached. If cases remained undecided, then we solicited the expert opinion of a third party.

4. Results

As indicated in Fig. 1, the number of papers published in each year over the 12-year period ranges from 22 to 68. Due to the possible time lag in reviewing and revising the submitted manuscripts and the scheduling of journal publications, it is justifiable to look at a three-year simple moving average for the publications. As expected, the values of the moving averages (23.67, 23.33, 22.67, 24.67, 26.67, 29, 33, 35, 42.67, and 52.67 applications) clearly demonstrate a steadily increasing trend.

Table 2 shows the number of authors by country and membership status of the Organization for Economic Co-operation and Development (OECD). There are a total of 733 researchers affiliated with different institutions in 45 countries. The largest number of authors are from Taiwan (129 or 17.6%), followed by China (including Hong Kong; 98 or 13.37%), the United States (83 or 11.32%), and India (68 or 9.28%). Together, these four countries account for more than half of the total number of authors. As OECD member countries represent more developed economies, Table 2 indicates that 344 of the researchers (46.93%) are from the 20 developed countries, and 389 of the researchers (53.07%) are from the 25 developing countries.

Our review indicates that, of the 402 articles, 42 (10.45%) are collaborations between authors from OECD and non-OECD countries. With regard to the type of affiliated institution, 376 of the articles (93.54%) were written by university professors and researchers, five (1.24%) were authored by industry practitioners and government officials, and 21 (5.22%) were jointly written by authors from both sectors.

As shown in Table 3a, only 10 out of the 21 journals had published articles on fuzzy set theory POM applications. The

Table 1
POM application areas by decision type (adapted from Jayaraman and Srivastava (1996)).

Decision type		
Unstructured	Semi-structured	Highly structured
Environment	Aggregate planning	Distribution
Process choice	Facilities layout	Inventory control
Process design	Facilities location	Maintenance
Product design	Job design	Purchasing
Quality planning	Long-term capacity planning	Quality control
	Long-term forecasting	Scheduling
	Project management	Short-term capacity planning
	Short-term forecasting	

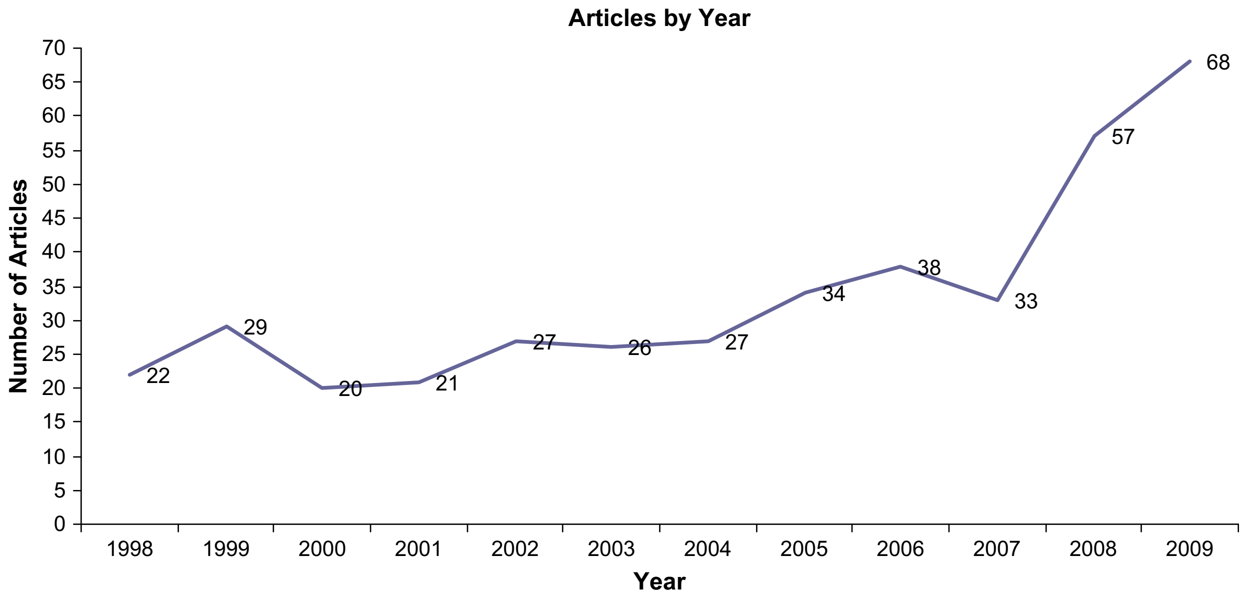

Fig. 1. Distribution of articles by year.

Table 2
Number of authors affiliated with countries and their OECD membership status.

Country	Number of authors	OECD	Country	Number of authors	OECD
Taiwan	129		Belgium	4	Member
China	98		Finland	3	Member
U.S.	83	Member	Indonesia	3	
India	68		Israel	3	
Turkey	36	Member	Netherlands	3	Member
Italy	33	Member	New Zealand	3	Member
U.K.	31	Member	Republic of Ireland	3	
Canada	27	Member			
Iran	25		Tunisia	3	
Japan	21	Member	Denmark	2	Member
Korea	21	Member	Oman	2	
France	19	Member	Sweden	2	Member
Spain	19	Member	Ukraine	2	
Singapore	13		Brazil	1	
Australia	12	Member	Colombia	1	
Malaysia	9		Egypt	1	
Mexico	7	Member	Jordan	1	
Portugal	7	Member	Nigeria	1	
Thailand	7		Philippines	1	
Poland	6	Member	Saudi Arabia	1	
Chile	5		Serbia and Montenegro	1	
Germany	5	Member			
Slovenia	5		United Arab Emirates	1	
Yugoslavia	5				

largest number of applications appears in the *International Journal of Production Research* and the *European Journal of Operational Research*, which account for 32.01% and 26.05% of the total reported applications, respectively. They are followed by *Computers and Industrial Engineering* and the *International Journal of Production Economics*, which together account for 30.77% of the reported applications. The remaining six journals published 11.17% of the total number of reported applications. It is surprising that the *International Journal of Operations and Production Management* and *Decision Sciences* published only two and one applications, respectively, and that 11 of the journals have not published any articles on the application of fuzzy set theory in POM.

The distribution of applications by journal and application area is presented in Table 3b. In terms of area of application, the *International Journal of Production Research* focuses more on short-term capacity planning, long-term capacity planning, and production design, whereas the *European Journal of Operational Research* places more emphasis on inventory control, aggregate planning, scheduling, and short-term capacity planning. The *International Journal of Production Economics* and *Computers and Industrial Engineering* focus on long-term capacity planning. It is interesting that some of the journals surveyed have published many more articles on particular application areas of fuzzy set theory than others. For example, the *International Journal of Production Research* has published more articles on short-term capacity planning, product design, facilities layout, quality control, and process design, whereas the *European Journal of Operational Research* features more articles on inventory control and aggregate planning.

The number and percentage of applications by application area are presented in Table 4. Long-term capacity planning (65 or 16.13%) accounts for the largest number of fuzzy set theory application areas, followed by short-term capacity planning (57 or 14.14%), inventory control (45 or 11.17%), product design (39 or 9.68%), aggregate planning (37 or 9.18%), and scheduling (34 or 8.44%). Together, these areas account for 68.74% of the total number of applications. The total percentage of applications in capacity planning, including short-term, aggregate, and long-term planning is 39.45%. The least popular research application areas are job design and long-term forecasting, which do not have any applications.

Table 5 shows the most commonly used methods for each application by the application area. A wide variety of techniques are utilized in different areas. The most common are inference, linear programming, and goal programming. Inference is used in maintenance, product design, and short-term forecasting, whereas linear programming and goal programming are used in aggregate planning and short-term capacity planning. Product design, which is the only unstructured type of application included in Table 5, does not really have a common method, but analytic hierarchy process (AHP), inference, and weighted average are used relatively more frequently than other methods.

Table 6 shows the distribution of applications by year and decision type. The structured decision type accounts for about half of the applications (48.64%), and the semi-structured and unstructured types of decisions comprise 34.49% and 16.87%, respectively. Taken together, the percentages taken up by the

Table 3a
Number and percentage of applications by journal.

Journal title	Number of applications[a]	Percentage
International Journal of Production Research	129	32.01
European Journal of Operational Research	105	26.05
Computers and Industrial Engineering	73	18.11
International Journal of Production Economics	51	12.66
Computers and Operations Research	14	3.47
Omega	12	2.98
Journal of Operational Research Society	11	2.73
IIE Transactions	5	1.24
International Journal of Operations and Production Management	2	0.5
Decision Sciences	1	0.25
Total	403	100.00

[a] One article has two applications.

Table 4
Number and percentage of applications by application area.

Application area	Number of applications[a]	Percentage
Long-term capacity planning	65	16.13
Short-term capacity planning	57	14.14
Inventory control	45	11.17
Product design	39	9.68
Aggregate planning	37	9.18
Scheduling	34	8.44
Facilities layout	18	4.47
Maintenance	18	4.47
Quality control	18	4.47
Distribution	16	3.97
Process design	11	2.73
Project management	11	2.73
Facilities location	8	1.99
Environment	6	1.49
Process choice	6	1.49
Short-term forecasting	6	1.49
Quality planning	5	1.24
Purchasing	3	0.74

[a] One article has two applications.

Table 5
Most common methods used in the applications by application area.

Application area[a]	Method	Number of applications
Aggregate planning	Fuzzy linear programming	9
	Fuzzy goal programming	5
Facilities layout	Fuzzy neural network	8
Inventory control	Fuzzy inventory/ EOQ/ EPQ models	21
Long-term capacity planning	Fuzzy AHP	9
Maintenance	Fuzzy inference	4
	Fuzzy logic controller	3
Product design	Fuzzy AHP	4
	Fuzzy inference	4
	Fuzzy weighted average	4
Quality control	Fuzzy control chart	5
Scheduling	Fuzzy GA/GA with fuzzy data	9
Short-term capacity planning	Fuzzy linear programming	8
	Fuzzy goal programming	4
Short-term forecasting	Fuzzy inference	3

[a] Application areas for which no common methods were identified are not reported.

Table 3b
Distribution of applications by journal and application area[a].

Journal title	LCP[b]	SCP	IC	PtD	AP	Sch	Fla	Main	QC	Dist	PM	PsD	Flo	Env	PC	SF	QP	Pur
International Journal of Production Research	18	23	3	17	9	11	11	7	11	2	1	8	0	3	4	0	1	0
European Journal of Operational Research	3	14	23	7	14	14	1	1	4	7	4	1	6	2	1	1	1	1
Computers and Industrial Engineering	16	7	5	8	8	3	4	7	2	3	4	0	0	1	0	3	1	1
International Journal of Production Economics	19	3	10	3	2	3	2	2	0	1	1	1	0	0	1	1	2	0
Computers and Operations Research	1	2	4	1	1	1	0	0	0	1	0	1	1	0	0	0	0	1
Omega	4	4	0	0	2	0	0	0	0	1	1	0	0	0	0	0	0	0
Journal of Operational Research Society	2	2	0	0	1	2	0	1	1	0	0	0	1	0	0	1	0	0
IIE Transactions	0	1	0	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0
International Journal of Operations and Production	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Management Decision Science	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	65	57	45	39	37	34	18	18	18	16	11	11	8	6	6	6	5	3

[a] One article has two applications.
[b] LCP—Long-term capacity planning, SCP—Short-term capacity planning, IC—Inventory control, PtD—Product design, AP—Aggregate planning, Sch—Scheduling, FLa—Facilities layout, Main—Maintenance, QC—Quality control, Dist—Distribution, PM—Project management, PsD—Process design, FLo—Facilities location, Env—Environment, PC—Process choice, SF—Short-term forecasting, QP—Quality planning, Pur—Purchasing.

Table 6
Distribution of applications by year and decision type.

Year	Unstructured	Semi-structured	Highly structured	Total[a]
1998	3 (13.64%)	4 (18.18%)	15 (68.18%)	22
1999	5 (17.24%)	7 (24.14%)	17 (58.62%)	29
2000	6 (30%)	4 (20%)	10 (50%)	20
2001	2 (9.09%)	9 (40.91%)	11 (50%)	22
2002	3 (11.11%)	8 (29.63%)	16 (59.26%)	27
2003	6 (23.08%)	7 (26.92%)	13 (50%)	26
2004	5 (18.52%)	8 (29.63%)	14 (51.85%)	27
2005	6 (17.65%)	12 (35.29%)	16 (47.06%)	34
2006	9 (23.68%)	11 (28.95%)	18 (47.37%)	38
2007	7 (21.21%)	13 (39.39%)	13 (39.39%)	33
2008	8 (14.04%)	23 (40.35%)	26 (45.61%)	57
2009	8 (11.76%)	33 (48.53%)	27 (39.71%)	68
Total	68 (16.87%)	139 (34.49%)	196 (48.64%)	403

[a] One article has two applications.

Table 7a
Number and percentage of applications integrated with AI technologies by year.

Year	Number of applications	Percentage
1998	3	3.09
1999	3	3.09
2000	9	9.28
2001	1	1.03
2002	7	7.22
2003	9	9.28
2004	4	4.12
2005	8	8.25
2006	11	11.34
2007	10	10.31
2008	13	13.40
2009	19	19.59
Total	97	100.00

Table 7b
Number and percentage of applications integrated with AI technologies by type.

Type	Number of applications	Percentage
Genetic/evolutionary algorithm	43	44.33
Neural network	36	37.11
Neural network and genetic/evolutionary algorithm	6	6.19
Expert system	5	5.15
Case-based reasoning and rule-based reasoning	3	3.09
Expert system and neural network	3	3.09
Expert system and genetic/evolutionary algorithm	1	1.03
Total	97	100.00

latter two decision types have increased, particularly between 2005 and 2009, whereas the percentage of structured decision applications decreased in the study period.

The number and percentage of applications that integrate the fuzzy set theory techniques with different types of AI technologies by year is shown in Table 7a. A total of 97 applications work accordingly, and their simple three-year moving averages (5, 4.33, 5.67, 5.67, 6.67, 7, 7.67, 9.67, 11.33, and 14 applications) clearly indicate an upward trend. Table 7b shows the number and percentage of applications integrated with AI technologies by type. The most common types of AI are genetic/evolutionary algorithms (43 or 44.33%) and neural networks (36 or 37.11%). Thirteen applications integrate fuzzy set theory with two types of AI technology. The number and percentage of applications integrated with AI technology by application area is presented in Table 7c. Scheduling, long-term capacity planning, facilities layout, and short-term capacity planning are the most common, whereas facilities location, process choice, purchasing, and quality planning are the least common.

Table 7c
Number and percentage of applications integrated with AI technologies by application area.

	Number of applications	Percentage
Scheduling	16	16.49
Long-term capacity planning	14	14.43
Facilities layout	10	10.31
Short-term capacity planning	10	10.31
Quality control	9	9.28
Inventory control	8	8.25
Aggregate planning	6	6.19
Process design	5	5.15
Product design	5	5.15
Maintenance	3	3.09
Short-term forecasting	3	3.09
Distribution	2	2.06
Project management	2	2.06
Facilities location	1	1.03
Process choice	1	1.03
Purchasing	1	1.03
Quality planning	1	1.03
Total	97	100

Table 8a
Top six most popular development tools.

	Number of applications
C/C++/Turbo C/Visual C	36
MATLAB	28
Lindo/Lingo	16
Basic/QBasic/Visual Basic	8
GAMS	5
Fortran/Fortran 77	3
Others	22
Total	118

A total of 118 applications report the names of the tools used in the development of the fuzzy set theory applications. Table 8a shows the top six most popular development tools, which include C/C++/Turbo C/Visual C, MATLAB, Lindo/Lingo, Basic/QBasic/Visual Basic, GAMS, and Fortran/Fortran 77. A further breakdown of the types of tools by year is presented in Table 8b. As can be seen, Fortran/Fortran 77 has not been used since 2001. A simple three-year moving average of the use of C/C++/Visual C/Turbo C (2.67, 2, 2, 2.33, 2.67, 2.67, 2.67, 2.67, 3.67, and 4.33 applications) and MATLAB (0, 0.33, 0.33, 1.33, 1.67, 2.33, 2.67, 2.33, 4, and 5.33 applications) indicates that the popularity of these tools is increasing.

5. Discussion

This section presents a discussion on the surveyed findings in the classified categories.

5.1. Publication

The number of published articles has increased steadily over the past 12 years, and this trend is expected to continue as the applicability of the fuzzy set theory technique in POM is fully

Table 8b
Distribution of applications by year and development tool.

Year	C/C++/Turbo C/ Visual C	MATLAB	Lindo/Longo	Basic/QBasic Visual Basic	GAMS	Fortran/ Fortran 77	Others
1998	3						
1999	2		1	1		2	3
2000	3						2
2001	1	1		1		1	1
2002	2			1			1
2003	4	3		1			
2004	2	2					2
2005	2	2	1				2
2006	4	4	3		1		3
2007	2	1	2				
2008	5	7	5	4	1		3
2009	6	8	4	0	3		5
Total	36	28	16	8	5	3	22

recognized by researchers worldwide. It is particularly interesting that both China and India have carried out a lot of research in this area. This is probably because they are the world's most populous nations and also have the fastest growing manufacturing economies.

It is quite unfortunate that most research is carried out in universities and that only a small percentage is jointly conducted by professors and practitioners. This trend may not be healthy, as it implies that less effort is being made to develop real-world applications. University professors and practitioners have their own unique expertise and experience, and collaboration between them would certainly enhance the overall quality and applicability of fuzzy set theory applications.

With regard to publication outlets, it seems that most academicians either prefer or find it more appropriate to publish their high-quality research output in just four leading journals: The *International Journal of Production Research*, the *European Journal of Operational Research*, *Computers and Industrial Engineering*, and the *International Journal of Production Economics*. It is unlikely that this phenomenon will change in the near future, as these four journals are well established and well recognized in this research area. In contrast, neither the *Journal of Operations Management* nor *Production and Operations Management*, two reputable POM journals, have published nay articles on fuzzy set theory or GAs (Chaudhry and Luo, 2005). Indeed, a computer-based search of these two journals concludes that they have published extremely few papers on any AI-related topic.

5.2. Applications and methods

This section discusses the POM application areas and the most commonly used fuzzy methods in each area.

5.2.1. Capacity planning

Capacity planning is a common application area of fuzzy set theory that accounts for about one-third of the surveyed articles. Surprisingly, however, the literature does not report this trend. As well-known, planning always involves a certain degree of uncertainty. Short-, intermediate-, and long-term capacity plannings are expected to involve various levels of vague and imprecise information, especially in areas such as the availability of raw materials, workforce levels, the assignment of jobs to machines (Abdi, 2009), production rates, level of inventory, customer requirements, due dates (Wang et al., 1999), and quality of results (Kulak and Kahraman, 2005). The use of fuzzy set theory is particularly suitable for long-term capacity planning, as it is more strategic and concerns less well-defined activities, which leads to greater uncertainty in the specification and solution processes involved (Kobbacy et al., 2007). The most common application areas include vendor/partner selection (24 applications) and manufacturing system investment/alternatives evaluation (12 applications). We expect the number of applications in these areas to increase in the near future, particularly in the area of vendor/partner selection, as our survey showed that of the 24 applications in this area, one each was published in 2002 and 2004, but five and nine were published in 2008 (e.g., Bottani and Rizzi, 2008; Bűyűkőzkan et al., 2008; Famuyiwa et al., 2008) and 2009 (e.g., Amid et al., 2009; Chen, 2009; Faez et al., 2009), respectively. No common applications were found in the areas of short-term capacity planning and aggregate planning, because most of the applications focus on production planning in a wide variety of manufacturing settings in different industries.

The most common fuzzy set theory technique used in long-term capacity planning is fuzzy AHP, which is mostly applied to vendor/partner selection issues. This is not surprising, as AHP is a powerful technique for addressing decision-making problems with multiple criteria and many alternatives. In the surveyed articles, fuzzy AHP was mainly used to tackle the fuzziness of data, such as expert opinions, which used to decide the relative weight of the decision criteria involved in selecting a vendor or partner (Bottani and Rizzi, 2008; Bűyűkőzkan et al., 2008; Efendigil et al., 2008).

The most popular techniques in both short-term capacity planning and aggregate planning are linear programming and goal programming. All of the applications in short-term capacity planning use single or bi-objective linear programming. However, in aggregate planning, more than half of the applications use multiple objective linear programming. This is to be expected, as aggregate planning is a medium-range type of capacity planning in production, and thus decisions always involve multiple objectives.

5.2.2. Inventory control

The application of fuzzy set theory in inventory control is considered to be one of the most attractive research areas (Du and Wolfe, 1997). This is particularly true now that supply chain and logistics management have become increasingly important in today's global environment. Fuzzy set theory has played a very important role in enhancing overall supply chain performance, as indicated in the nine studies identified in our survey (Petrovic et al., 1998, 1999, 2008a; Petrovic, 2001; Giannoccaro et al., 2003; Bogataj and Usenik, 2005; Haq and Kannan, 2006; Xie et al., 2006; Handfield et al., 2009).

Twenty-one applications were identified that utilize various types of fuzzy inventory models. In these models, fuzzy set theory is applied to deal with parameters that involve risk, uncertainty, or ambiguity. The more typical parameters are demand quantity, ordering costs, holding costs, lead time, and backorders. Less common ones include defective costs (Chen and Chang, 2008a), defective rates (Chang, 2004), penalty costs (Handfield et al., 2009), the price of merchandise (Yao et al., 2003), outdating costs (Katagiri and Ishii, 2002), storage areas (Mondal and Maiti, 2002), and supplier yield (Handfield et al., 2009).

5.2.3. Product design

Of the more popular fuzzy set theory application areas in POM, product design is the only unstructured type. This is quite unexpected, as fuzzy set theory is considered to be a powerful tool that handles uncertainties well. Our survey further indicates that about 60% of the published articles on product design are on the benefits of fuzzy quality function deployment (QFD). QFD is a design tool that helps the manufacturing industry to maintain a competitive edge in the global marketplace. This research area has received a great deal of attention because linguistic variables and triangular fuzzy numbers can effectively represent imprecise design information. So far, the results of these studies have proved very promising (e.g., Chen and Ngai, 2008; Lai et al., 2008; Lee et al., 2008).

Surprisingly, among the 39 applications in the area of product design, a wide variety of fuzzy methods are used. A total of 30 methods were identified, with the most common being AHP (Kwong and Bai, 2003; Bűyűkőzkan and Feyzioglu, 2004; Ayağ, 2005; Kahraman et al., 2006), the weighted average method (Vanegas and Labib, 2001; Bűyűkőzkan and Feyzioglu, 2004; Liu, 2005; Chen et al., 2006), and the inference approach (Fung et al., 1998; Chen et al., 2004; Nepal et al., 2005; Li et al., 2009). The weighted average method deals mainly with technical attribute requirements, whereas the inference approach is used to handle linguistic variables, such as customer requirements, performing evaluations based on fuzzy "If–Then rules."

5.2.4. Scheduling

Research on the application of fuzzy set theory in scheduling began as early as 1979, and it was at one time deemed to be the most active topic at the crossroads of operations research and fuzzy sets (Fortemps, 2003). In most real-world scheduling applications, durations, processing times, and constraints are imprecise. Even when time parameters are controllable, they are often linked to product quality or customer satisfaction, and may thus become flexible data. Fuzzy set theory has a unique ability to model these types of problems efficiently. The application of fuzzy set theory in this domain has remained prevalent over the past 12 years, with the most common research areas being job shop/flow shop (Murata et al., 1998; Hong and Chuang,1999; Macchiaroli et al., 1999; Sakawa and Kubota, 2000; Cheng et al., 2001; Lee et al., 2002; Petroni and Rizzi, 2002; Sudiarso and Labib, 2002; Yun, 2002; Allet, 2003; Bonfatti et al., 2006; Petrovic et al., 2008b; Tavakkoli-Moghaddam et al., 2008), flexible manufacturing systems (Yu et al.,1999; Lee et al., 2001; Li et al., 2006; Srinoi et al., 2006), and product development (Wang, 1999; Chanas and Kasperski, 2003; Wang, 2004; Anglani et al., 2005). Our survey shows GA to be the most common technique used in scheduling applications, as it can be used to search for an optimal or near-optimal solution over a fuzzy objective function with fuzzy scheduling data. GA is most commonly applied in job shop scheduling (Sakawa and Kubota, 2000; Yun, 2002; Petrovic, et al., 2008b) and fault-tolerant fabric-cutting scheduling (Kwong, et al., 2006; Mok et al., 2007).

5.2.5. Facilities layout

Of the 18 applications of fuzzy set theory in facilities layout, 11 relate to part-machine grouping and cell formation. This is not surprising, because cellular manufacturing (CM) is recognized as the cornerstone of the manufacturing cell formation technologies and a fundamental step in the design of a CM system is to create part families and their associated machine cells. Fuzzy set theory plays an important role here, as the relationships between parts and machines can be expressed by fuzzy membership values. Furthermore, all possible factors, both qualitative and quantitative, which affect the performance of CM can be reduced to membership values.

The most commonly used technique in this is the neural network, with nine applications, six of which relate to part-machine grouping and cell formation. Specifically, fuzzy ART neural networks are used to handle manufacturing factors such as operation sequences with multiple visits to the same machine and multiple identical machines (Won and Currie, 2007); to identify families of parts with a similar sequence of operations (Suresh et al., 1999; Park and Suresh, 2003); and to solve binary and non-binary part-machine incidence matrices (Peker and Kara, 2004). Kuo et al. (2001) used a fuzzy self-organizing feature map neural network to cluster parts into several families based on image captured from a vision sensor, and Dobado et al. (2002) developed a fuzzy min–max neural network to address binary part-machine incidence matrices. These studies indicate that neural networks can be more accurate, more consistent, faster in execution, and easier to implement than other clustering techniques.

5.2.6. Maintenance

Maintenance activities fall into the two broad categories of corrective maintenance and preventive maintenance. In the majority of articles in the survey, fuzzy set theory was used to deal with preventive maintenance due to its ability to manage decision-making under uncertainty. Some typical examples are tool condition monitoring in face milling operations (Dutta et al., 2000), condition monitoring for hard turning in machine operations (Kothamasu et al., 2005), preventive maintenance in manufacturing control systems (Yuniarto and Labib, 2006), and equipment prioritization for preventive maintenance (Khanlari et al., 2008).

The most common fuzzy techniques used in maintenance are the inference approach and logic controllers. Both basically make use of fuzzy rules to improve decision making, especially when maintenance problems do not have clear or robust decision criteria. This rule-based approach is powerful in that it can interpret linguistic variables that normally cannot be explicitly analyzed or statistically expressed. Applications that use the inference approach include tool breakage detection in end milling operations (Huang and Chen, 1998), defect spatial pattern recognition in semiconductor fabrication (Hsieh and Chen, 2004), automated sensor self-validation for cupola furnaces (Mahmoud et al., 2004), and equipment prioritization for preventive maintenance (Khanlari et al., 2008). Those that use fuzzy logic controllers include machine maintenance in roof systems production (Labib et al., 1998), temperature control in resin adhesive production (Nagarajan and Kumar, 2001), and preventive maintenance in manufacturing control systems (Yuniarto and Labib, 2006).

5.2.7. Quality control

There are a wide variety of applications of fuzzy set theory in quality control, with the most commonly used technique being the control chart. The main function of this technique is to handle unstable data in the production process, and it has been successfully implemented in and has improved quality control in various aspects of production processes. Applications that use chart control include fuzzy-soft learning vector quantization for control chart pattern recognition (Yang and Yang, 2002), the detection simplification of out-of-control situations by reducing the number of charts and chart rules for typical unnatural patterns (Tannock, 2003), the economic design of variable parameters QUOTE and control charts for soda pop production processes (Chen and Chang, 2008b), and the multivariate process monitoring of multi-dimensional linguistic data in porcelain manufacturing (Taleb and Limam, 2002; Taleb, 2009).

5.2.8. Distribution

Fuzzy set theory is most commonly applied in distribution to transportation problems, with a total of five applications identified. Three of those used hypothetical data for analyses, and dealt with multi-objective problems (Das et al., 1999; Abd El-Wahed and Lee, 2006) and problems with inequality and equality constraints (Liu and Kao, 2004). The other two involve the transportation problem of housing materials manufacturers (Sakawa et al., 2002) and minimal cost flow problem in hazardous materials transportation (Ghatee et al., 2009). In most of these applications, fuzzy set theory was used either to derive the fuzzy objective value of the transportation problem or to have the cost coefficients and the supply/demand quantities expressed as fuzzy values, or both. Further, although there are 16 applications in the area of distribution, no commonly used fuzzy technique was identified.

5.2.9. Process design

In the area of process design, most applications are associated with the design of manufacturing systems. Due to the variety of data sources and continuous goal changes, the information available in process design is always imperfect. Fuzzy set theory addresses the uncertainty, inaccuracy, and vagueness of objectives and solutions that are of particular concern in process design. The five identified applications are flexible manufacturing system design in clock production (Chan et al., 2000), manufacturing system design for small and medium enterprises (Gien et al., 2003), automated flow shop manufacturing system design (Monfared and Yang, 2005), printed circuit board manufacturing plant design (Anand et al., 2006), and multiproduct batch plant design (Aguilar-Lasserre et al., 2009).

5.2.10. Project management

Of the 12 applications in project management, the most common relate to R&D project evaluation (Hwang and Yu, 1998; Mohanty et al., 2005; Wang and Hwang, 2007; Fernandez et al., 2009), engineering/technology investment evaluation (Hwang, 2004; Tan et al., 2006), and critical path analysis (Slyeptsov and Tyshchuk, 2003; Chen, 2007). R&D project evaluation involves a high degree of decision-making uncertainty due to the subjectivity of judgments about the impacts and relationships among the attributes in an R&D project. Typical attributes are organization, market, environment, risk, and type of research (Mohanty et al., 2005; Fernandez et al., 2009).

5.2.11. Facilities location

A total of eight applications in facilities location were found in our survey. Three studies used hypothetical data (Liang, 1999; Chou, et al., 2008; Wen and Iwamura, 2008) without much detailed information. The other five applications comprise locating possible drilling sites for oil (Zhu et al., 1999), selecting distribution centers for a firm (Fernández-Castro and Jiménez, 2005), determining emergency service vehicle location (Araz et al., 2007), selecting office locations (Ma and Li, 2008), and selecting defensive locations (Uno and Katagiri, 2008). Most of these applications were reported in recent years. A variety of fuzzy techniques were used in these applications, including AHP (Zhu et al., 1999), multiple criteria decision-making algorithms (Liang, 1999), integer linear programming (Fernández-Castro and Jiménez, 2005), goal programming (Araz et al., 2007), ranking (Ma and Li, 2008), the satisfying method (Uno and Katagiri, 2008), the simple additive weighting system (Chou et al., 2008), and simulation (Wen and Iwamura, 2008).

5.2.12. Environment

Environmental issues are a relatively new area of production research, although they have gained attention in many industries due to market pressures and environmental regulations. Only six applications were identified: environmental impact assessment for paper cutter manufacturing (Hui et al., 2002), the identification of environmental improvement options in office table design (Bovea and Wang, 2003), environmental performance assessment in the supplier selection process (Humphreys et al., 2006), carbon-tax design in the residential sector (Kunsch and Springael, 2008), sustainable production indicator evaluation for healthcare service providers and product manufacturers (Tseng et al., 2009), and sustainability policy evaluation for renewable energy (Munda, 2009).

5.2.13. Process choice and quality planning

Process choice and quality planning are unstructured types of decisions, with only six and five published applications, respectively. The process choice applications comprise performance-based control for machining processes (Bin et al., 1999), productive performance evaluation in preprint insertion manufacturing processes (Triantis et al., 2003), rapid tooling manufacturability evaluation (Nagahanumaiah et al., 2007), reconfigurable manufacturing system selection for an automobile components production company (Singh et al., 2007), knowledgeable manufacturing system mode selection (Yan and Xue, 2007), and the performance optimization of an integrated process planning and scheduling model in outsourcing (Chan et al., 2009). In the area of quality planning, the applications include quality-based program selection for a paper handkerchief manufacturer (Noci and Toletti, 2000), logistics processes and customer satisfaction improvement for a piping components design and manufacturing firm (Bottani and Rizzi, 2006), aggregated importance determination of engineering characteristics in digital camera design (Kwong et al., 2007), stream water quality management in a river (Qin et al., 2007), and quality costing in process industries (Sharma et al., 2007).

5.2.14. Forecasting

Surprisingly, our survey did not find any applications in long-term forecasting. Six studies were identified on fuzzy set applications in short-term forecasting, three of which were related to sales forecasting (Thomassey et al., 2005a, 2005b; Tseng, 2008) and three of which dealt with cost/time prediction in manufacturing processes (Jahan-Shahi et al., 1999, 2002; Chen, 2008).

5.2.15. Purchasing

Only three applications were identified in the area of purchasing. Shiromaru et al. (2000) applied a fuzzy satisfying method to deal with the vagueness of the goals involved in a coal purchase planning problem. A Bayesian network involving fuzzy parameters was used by Li and Kao (2005) to model the relationship between just-in-time purchasing techniques and firm performance. Rau et al. (2009) adopted fuzzy technology to automate purchase order management processes in B2B transactions. All of these studies indicate that it is feasible to apply fuzzy set theory to these applications, and that positive results are produced.

In summary, the application of fuzzy set theory is relatively uncommon in some areas of POM, but that certainly does not mean that it is an inappropriate technology for these areas. We believe that the popularity of development tools and potential integration with other AI technologies may encourage researchers to exploit the application of fuzzy set theory in other POM areas.

5.3. Decision type

The substantial increase in the percentage of publications on both semi-structured and unstructured types of applications implies that researchers have developed a better understanding of the unique features of fuzzy set theory and are trying to exploit these features as fully as possible. The applications of fuzzy set theory are no longer restricted to traditional and structured areas, such as scheduling and inventory control. Of the semi/unstructured types of application published in the past three years, the environment, facilities location, long-term capacity planning, process choice, project management, and quality planning each account for about 45–67% of the total number of articles published in the 12-year period surveyed. It is likely that the increase in trend in these areas will continue, especially as the majority of the applications have been successfully implemented.

5.4. AI technology integration

In their recent study, Kobbacy et al. (2007) stated that the number of publications on hybrid AI approaches is surprisingly low and that there is no clear increase in trend. This finding contradicts our survey results to a certain extent, as we discovered an increased number of systems that integrate fuzzy set theory with other AI techniques, the most common types being the integration of fuzzy set theory with genetic or evolutionary algorithms and neural networks.

There has been little discussion of the integration of fuzzy set theory and genetic or evolutionary algorithms in the literature, although it is the most popular type of integration according to our survey. Its popularity is largely due to its successful implementation in scheduling, where it is used in about 26% of applications. The synergy of GA and fuzzy set theory is effective for typical scheduling applications, because fuzzy set theory can perfectly model variables such as due dates, processing times, and tardiness, and a GA can optimize a fuzzy objective function (Sakawa and Kubota, 2000; Wang, 2004; Mok et al., 2007; Petrovic et al., 2008b). The application of the integration of fuzzy set theory and neural networks in POM has also proved feasible, and discussions of different forms of synergistic integration can be found in the literature (e.g., Du and Wolfe, 1997; Hellendoorn, 1997; Kobbacy et al., 2007).

Only a handful of applications integrate fuzzy set theory with more than one type of AI technology, which indicates that the development of hybrid systems in POM applications is still in the embryonic stage. Each AI technology has its own unique strengths and has been successfully applied in a variety of POM areas. For example, fuzzy set theory is capable of reasoning under conditions of uncertainty, neural networks are good at classification and estimation, GAs are capable of optimization, and expert systems are good at the representation of knowledge. Because these unique capabilities complement each other to generate synergistic effects, we posit that hybrid systems have great potential to tackle the more complicated and unstructured types of application.

In terms of the areas in which hybrid systems are currently applied, scheduling and long-term capacity planning are relatively more common. As has been mentioned, the integration of fuzzy set theory with GAs plays an important role in the successful development of scheduling applications. It is interesting that fuzzy set theory appears to integrate well with neural networks, GAs, and case-based reasoning in long-term capacity planning. Of the 14 applications in long-term capacity planning, six are related to the selection of vendors or logistics companies (Crispim and de Sousa, 2009; Efendigil et al., 2008; Faez et al., 2009; Işiklar et al., (2007); Verma and Tiwari, 2009; Wang and Lin, 2006) and four are associated with different types of applications in supply chain management, including global logistics mode selection (Sheu, 2008), information distortion (Balan et al., 2009), multistage design (Xu et al., 2009), and supplier reliability (Mahnam et al., 2009).

5.5. Development tool

Finally, it was somewhat unexpected to find that none of the popular fuzzy set theory software packages were used to develop POM applications. FuzzyTECH, a well-known development tool, was used in only two applications (Bogataj and Usenik, 2005; Becher, 2009). The most popular tools are still programming languages, such as C and its extension, and mathematical tools and optimization software, including MATLAB and Lindo/Lingo. The use of programming languages is more flexible in terms of development that meets the specific needs of the application, but it can also be more complex, expensive, and time-consuming, and is less user-friendly. It is hoped that more powerful and user-friendly fuzzy set theory development software will be made available in the near future so that researchers and practitioners can tap into this state-of-the-art technology for the development of applications in POM.

6. Limitations of the study

All research studies have their limitations, and ours is no exception. First, readers should be cautious in interpreting the results, as the findings are based on data collected from only 21 U.S. and European academic business journals. AI and related journals were not covered by the survey, although we discuss the application of AI techniques in POM, and thus the results do not reflect all of the available fuzzy set theory applications. Second, due to the lengthy journal review process, the fuzzy set theory applications reported in the surveyed articles most probably do not represent the actual development of fuzzy set theory in the real world. Third, we only reviewed journal articles. Conference proceedings and doctoral dissertations were excluded, as we assume that such high-quality research will eventually be published in academic journals. However, our journal selection decision was based on the work of Chaudhry and Luo (2005), whose study takes into account the results of three published studies on the ranking of POM journals. We thus consider this list to be a good representation of reputable POM journals.

Another limitation of our study is that we mainly focus on the historical trends in fuzzy set theory research in POM application areas, and do not analyze how fuzzy set theory could be applied in different types of POM applications. We suggest that future research be conducted to gain an in-depth understanding of how fuzzy set theory can help to improve efficiency and effectiveness in different POM areas, and to explore the possible role that fuzzy set theory might play in less popular POM applications.

7. Conclusions

This research has surveyed 402 articles published in leading POM and business journals between 1998 and 2009 on the application of fuzzy set theory techniques in different areas of POM. The main findings can be summarized as follows:

(1) There has been an increase in the number of applications of fuzzy set theory in POM, with the most popular areas of application being long-term capacity planning, short-term capacity planning, inventory control, product design, aggregate planning, and scheduling.
(2) No one type of fuzzy technique is used in POM applications, but some application areas make more use of particular techniques.
(3) There has been an increase in the percentage of applications that address semi/unstructured types of POM problems.
(4) There has been an increase in the number and percentage of applications that integrate the fuzzy set theory technique with different types of AI technologies, the most common of which are genetic or evolutionary algorithms and neural networks.
(5) The use of C and its extension for the development of applications has increased over the past 12 years, but no popular fuzzy set theory software package has been developed specifically for POM applications.
(6) The largest number of applications appears in the *International Journal of Production Research*, the *European Journal of Operational Research*, *Computers and Industrial Engineering*, and the *International Journal of Production Economics*.
(7) Most of the research was carried out in universities, and there have been very few joint research projects conducted by professors and practitioners.

Our survey identifies several trends, some of which are unexpected and some of which contradict past findings. It is hoped that the results of this study will highlight the importance of fuzzy set theory in POM, offer insights into its current role in various POM applications, provide valuable information about publication channels, and ultimately stimulate the research interest of both academicians and practitioners in this area.

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