Review

Fifteen years of grey system theory research: A historical review and bibliometric analysis

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ABSTRACT

The grey system theory, identified as one of the developed multiple attribute decision-making techniques, has been published by and indexed in over 300 internationally recognized refereed journals. The objective of this study is to conduct a bibliometric study on publication and citation patterns of grey system theory published from 1996 to 2010 through a systemic search using the ISI web-based databases with a specific focus on grey relational analysis (GRA) and grey prediction. Results of the study demonstrate that there has been a substantial increase in the number of peer-reviewed papers on GRA or grey prediction indexed by the ISI Web of Knowledge. Also, citation analysis was used to examine the contributions of GRA and grey prediction studies. This bibliometric analysis would provide a ready reference for scholarly works on GRA and grey prediction, and serve as an informative summary kit for future research works.

1. Introduction

In 1982, Professor Deng Julong, a Chinese scholar, initiated the grey system theory (GST) under the assumption that circumstantial information obtained by decision makers or researchers may be partially unknown, uncertain or incomplete (Deng, 1989; Wen, Chao, Chang, Chen, & Wen, 2009). As an emerging multiple attribute decision-making tool which requires a limited knowledge and understanding of an unascertained system to solve problems, make good estimations or predictions, this theory soon caught the attention of scholars and practitioners from various discipline roots and scientific fields in the Chinese societies. During the past three decades, flourishing numbers of research studies on grey systems have been indexed in internationally recognized refereed journals and conference proceedings like *SCI*, *EI*, and *ISTP* (Lin & Liu, 2004; Liu & Lin, 1998). Bibliometric method had been used by Liu and Lin (1998) to compare publication performance and plot the up-trending developments of emerging studies on fuzzy mathematics, grey systems theory, and rough set theory through a search of ISI and EI Compendex databases. Liu and Forrest (2007) further investigate the growth scientific impact of GST as judged by China National Knowledge Infrastructure (CNKI) and EI Compendex databases. Accordingly, scientific research utilizing GST were carried out by scholars around the globe, such as China, United States, England, Germany, Japan, Australia, Canada, Austria,

Russia, Turkey, the Netherlands, Iran, and others (Lin & Liu, 2004; Liu & Lin, 1998). The 2000s saw the widespread popularity of research studies adopting the GST as an emerging multi-attribute decision making tool, supported by new academic organizations and published by over one thousand different professional journals (Wen et al., 2009). The three-odd decades of specific methodological significance contributed by GST has yielded insights into many applications, ranging from model construction, relational analysis, prediction and decision making of systems that are conventionally viewed as incomplete and indefinite (Deng, 1989; Lin & Liu, 2004; Wang, 2000).

Bibliometrics, a type of research method used in library and information sciences based on knowledge-based system and diffusion theory, have been widely applied to approximate scientific progress and paradigm changes through detections of publication productivity and analysis of citation data within a given topic, field, institute, or country (Ho, 2008; Lindsey, 1980; Osareh, 1996). By studying literature generated by bibliometric tools, a comprehensive and informed understanding of previous research often prompts thinking about what needs to be done next. In this respect, the present synthesized review of existing literature in the GST aims to offer a comprehensive picture of what GST researchers have done in the past and contribute to the ongoing forward-looking spread of the GST in different fields for future research.

Differing from the aforementioned two bibliometric studies on GRA in which up-trending developments of studies on three uncertain systems were compared and then sustaining development of GST was explored, the present study offers a systemic review of the literature from 1996 to 2011 with the primary aim of

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Table 1
Language of publications in GRA and grey prediction.

Languages	GRA		Languages	Grey prediction	
	Counts	% of total		Counts	% of total
English	450	99.33	English	141	98.601
Chinese	3	0.662	Chinese	1	0.699
			Spanish	1	0.699

ascertaining the quantity and spread of published GST papers available through the 2011 edition of ISI web-based databases with a specific focus on peer-reviewed journal articles focusing on grey relational analysis (GRA) and grey prediction – two widely applied models by scholars from around the world. To gauge a coherent situated understanding of a set of GST studies as a whole throughout the past 15 years, the study adopted bibliometric methodology systematically evaluate not only the publication performance of GRA and grey prediction, covering the total numbers of publication, language, authorship, and page counts, but also the publication trends, covering numbers of publication by publication years, annual publication outputs by countries/territories, subject areas and source titles. To trace the citation aspects of GRA and grey prediction studies, the top 10 most frequently cited articles were listed with publication years, source titles and their impact factors, aiming at obtaining an overview of GST spanning from January 1, 1996 to December 31, 2011.

2. Materials and method

The study aims to analyze journal articles contained in ISI Web of Knowledge covering three citation indexes – the *Social Sciences Citation Index*, the *Science Citation Index*, and the *Arts & Humanities Citation Index* – during the time span of 1996 to 2011, the earliest year when the database was available to the best possible full text availability to date. Searches were done using two variant keyword combinations: "grey relational analysis" or "gray relational analysis", and "grey prediction" or "gray prediction" under the search "Topic" section through a cutoff date of December 31, 2011. To avoid disparity in research focus, proceeding papers, reviews and meeting abstracts were excluded from the document types. The analyses were performed by using the "analyze" function of the ISI web-based software according to publication years, subject areas, countries/territories, and source titles. Bibliographic information retrieved from the ISI web-based software provided detailed records of counts, percentages and bar charts as a ready data source for further tabulations in the present bibliometric analysis. Because journal articles represented the majority of documents that were also peer-reviewed within this field, only journal articles were considered for the current bibliometric evaluation.

3. Preliminary results on publication performance

3.1. Total numbers of publications

There were 482 publications that met the selection criteria of "grey relational analysis" or "gray relational analysis" topic search. As journal articles represented the majority of document types that were also peer-reviewed within this field, 453 articles (94%) were identified and further analyzed in this study. No records were found under the *Arts & Humanities Citation Index*.

With regard to the selection criteria of "grey prediction" and "gray prediction", the ISI web-based software indentified a total of 150 records, with a total of 143 records meeting the selection criterion of peer-reviewed journal articles. No records were found under the *Arts & Humanities Citation Index*.

3.2. Language of publication

The dominant language in which studies on grey relational analysis and grey prediction was English. Of the 453 grey relational analysis articles, 450 (99.33%) were published in English, with 3 in Chinese (0.66%). Of the 143 articles within the field of grey prediction, 141 articles (98.6%) were published in English, with 1 each (0.70%) in Chinese and Spanish. Grey system theory was started in China; however, of the total of 596 articles examined in this present study, only 4 (0.67%) were published in Chinese. In total, 591 articles (99%) were published in English (Table 1).

3.3. Authorship

Average authors per study on grey relational analysis from 1996 to 2011 was 2.92. The 453 published papers were authored by 1323 authors. Of the 453 papers, 56 (12.4%) were written by a sin-
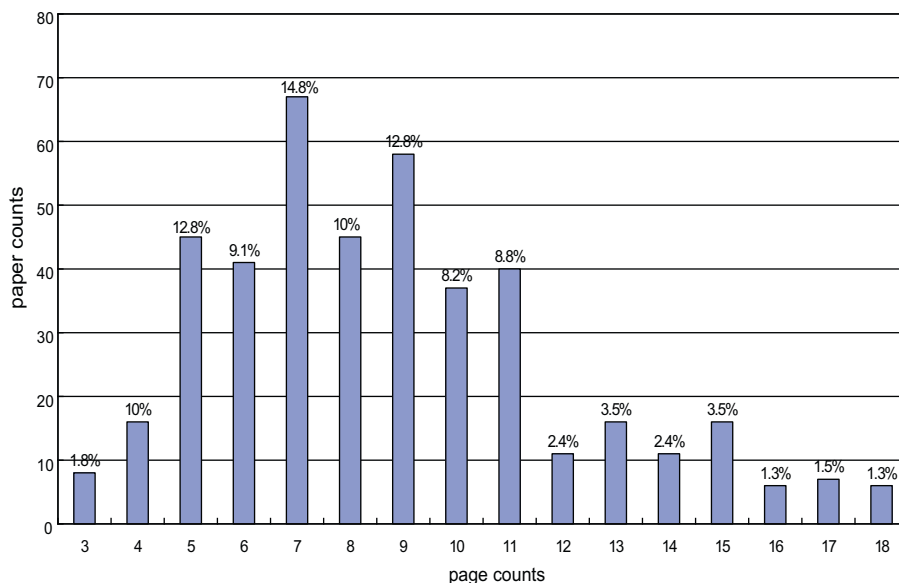

Fig. 1. Frequencies and percentages of page counts of publications on GRA studies.
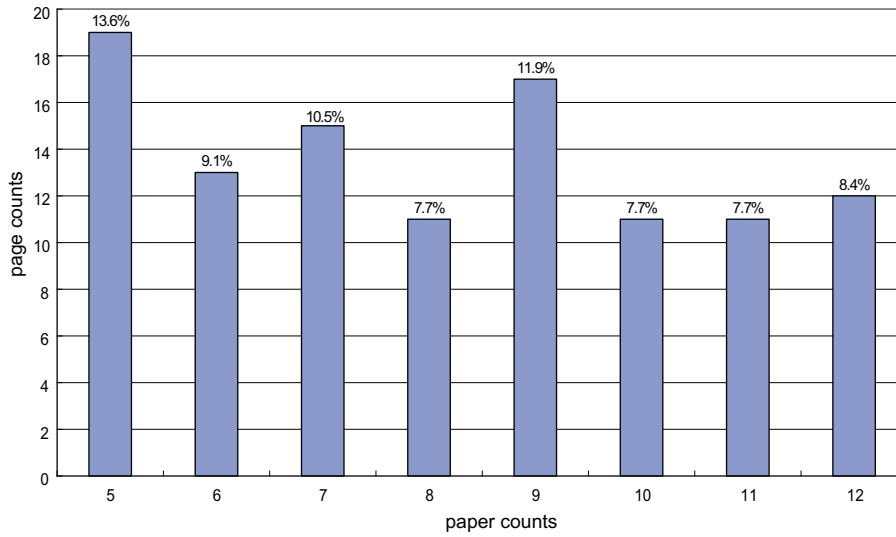
Fig. 2. Frequencies and percentages of page counts of publications on grey prediction studies.

gle author, 134 (29.6%) by 2 authors, 139 (30.7%) by 3 authors, 68 (15%) by 4 authors, 40 (8.8%) by 5 authors, 10(2.2%) by 6, 3(0.7%) by 7 authors, 2 (0.4%) by 8 authors, and 1 (0.2%) by 13 authors. The most-frequent number of authors was 2–3, accounting for 273 (60.3%) papers.

The 143 studies on grey prediction from 1996 through 2011 were authored by 380 authors. The average was 2.66. Of the 143 papers published, 18 (12.6%) were contributed by one author, 52 (36.4%) written by 2 authors, 40 (28%) by 3 authors, 28 (19.6%) by 4 authors, and 1 (0.7%) by 6 authors. The most-frequent number of authors was 2 to 4, accounting for 120 (84%) papers.

3.4. Page counts

There were 4214 pages in the total of 453 studies on grey relational analysis for an average of 9.39 pages per paper. Among these papers on grey relational analysis in ranking order, 67 papers (14.8%) were consisted of 7 pages, 58 (12.8%) of 9 pages, 45 (10.0%) of 5 pages and 8 pages respectively, 40 (8.8%) of 11 pages, 37 (8.2%) of 10 pages. Seventeen papers (15.5%) were consisted of pages ranging from 11 to 19; the remaining 23 papers (5.1%) were less than 4 pages (Fig. 1).

With respect to page counts of studies on grey prediction from 1996 through 2011, there were 1348 pages in the total of 143 papers for an average of 9.42 pages per paper. Among these papers on grey prediction in ranking order, 19 papers (13.3%) were consisted of 5 pages, 17 (11.9%) of 9 pages, 15 (10.5%) of 7 pages, and 13 (9.1%) of 6 pages, the 12 (8.4%) of 12 pages, 11 of 8, 10 and 11 pages respectively. Twenty-four papers (16.8%) were with more than 12 pages. The remaining 9 papers (6.3%) were less than 4 pages. Of the total of 596 studies examined in the present study, the majority of papers were with page counts ranging from 5 to 12. Few papers were found consisted of more than 20 pages (Fig. 2).

4. Results of publication trend analysis in grey system theory

Having indentified the preliminary publication performance, the present study next examines publication trends of GST by mapping distributions of publications by years across the categories of corresponding authors' countries/territories, subject areas, and source titles.

Table 2
Distribution of GRA and grey prediction studies by publication years.

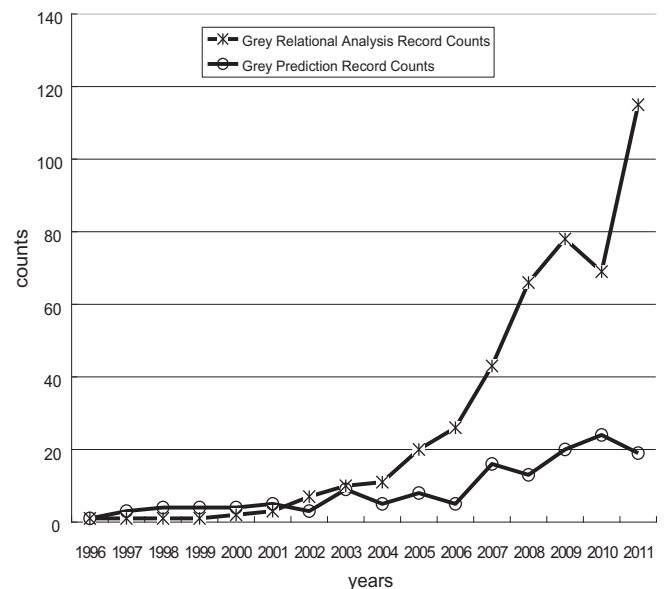| Publication years	GRA		Grey prediction	
	Counts	% of 453	Counts	% of 143
1996	1	0.221	1	0.699
1997	1	0.221	3	2.098
1998	1	0.221	4	2.797
1999	1	0.221	4	2.797
2000	2	0.442	4	2.797
2001	3	0.662	5	3.497
2002	7	1.545	3	2.098
2003	10	2.208	9	6.294
2004	11	2.428	5	3.497
2005	20	4.415	8	5.594
2006	26	5.519	5	3.497
2007	43	9.492	16	11.189
2008	66	14.570	13	9.091
2009	78	17.219	20	13.986
2010	69	15.232	24	16.783
2011	115	25.386	19	13.287

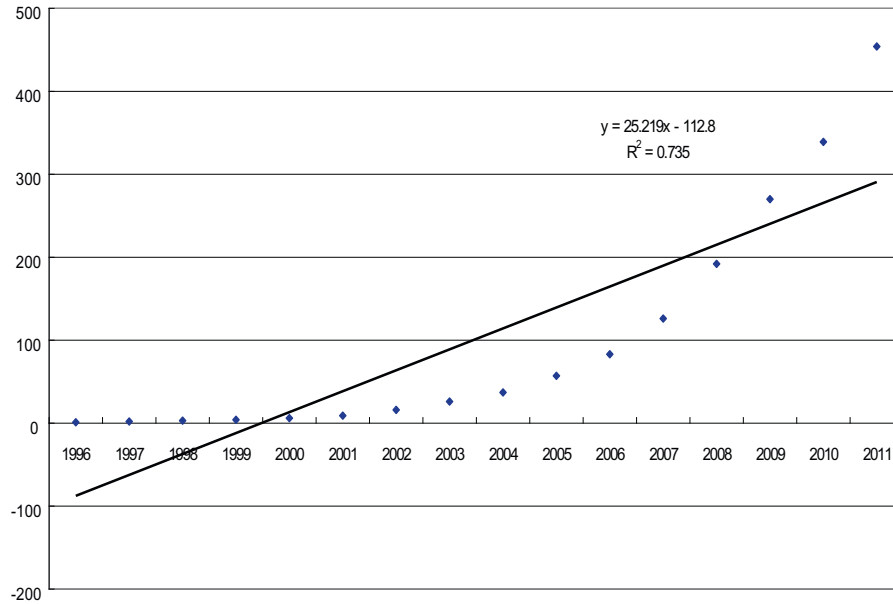**Fig. 3.** Annual publication outputs of GRA and grey prediction studies.

Fig. 4. The linear annual growth rate of GRA research.

4.1. Distribution of GRA and grey prediction studies by publication years

Table 2 displays GRA and grey prediction studies by publication years. Fig. 1 depicts the number and percentage of annual publications outputs of GRA and grey prediction studies. The first identified journal article on GRA indexed by ISI Web of Knowledge was published in the February 1996 issue of *Fuzzy Sets and Systems*. The majority of GRA studies were published after 2002. Fig. 3 shows a constantly increasing number of GRA studies since 2005, with a slight drop in the year of 2010.

As for grey prediction studies, the first identified entry indexed by ISI Web of Knowledge was published in the April 1996 issue of *International Journal of Machine Tools and Manufacture*, with the majority published after 2003. This parallels the trend for GRA publications indexed in ISI Web of Knowledge. A constantly increasing number of GRA studies were found since 2005, with a slight drop in the year of 2011 (Fig. 3).

The cumulative number of publications on GRA and grey prediction increased steadily as well. In 1996, one document was found on GRA and grey prediction respectively, while in 2003 the cumulative number of publications on GRA was 26 and on 33 on grey prediction. Significant correlations between yearly cumulative number of publications and the year published was presented in Figs. 4 and 5, revealing a significant linear relation with a high coefficient of determinations ($r^2 = 0.735$ for GRA; $r^2 = 0.894$ for grey prediction). The linear growth models suggested that a constant growth rate was sustained for yearly publications, reflecting an exponential growth typical of any emerging field of study.

4.2. Distribution of GRA and grey prediction studies by countries/territories

Annual outputs of authors' corresponding countries/territories where GRA studies and grey prediction studies were carried out over time are presented in Table 3. The six top productive coun-
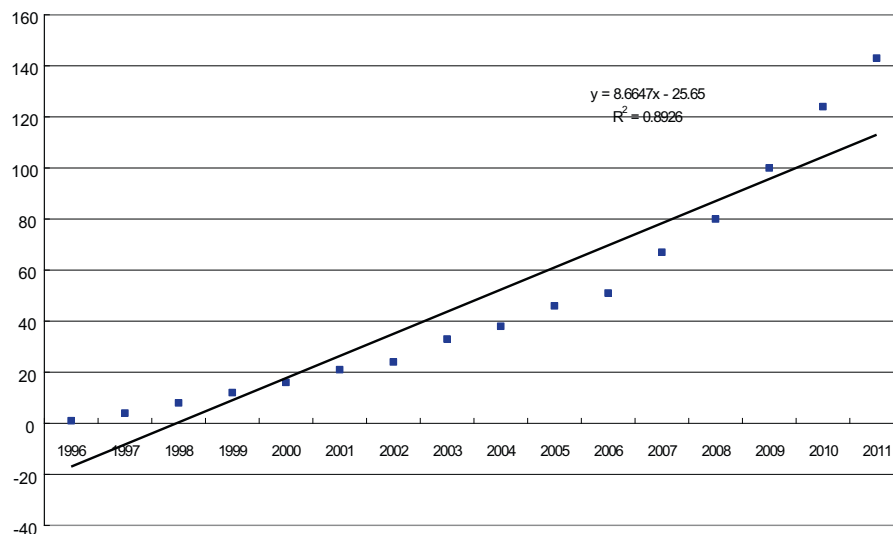

Fig. 5. The linear annual growth rate of grey prediction research.

Table 3
Publication countries/territories on GRA and grey prediction studies.

GRA				Grey prediction			
Countries/territories	Counts	% of total	Rank	Countries/territories	Counts	% of total	Rank
Taiwan	226	49.670	1	Taiwan	88	61.538	1
China	130	28.571	2	China	38	26.573	2
India	59	12.967	3	USA	5	3.497	3
Turkey	13	2.857	4	Japan	4	2.797	4
USA	8	1.758	5	Turkey	4	2.797	4
South Korea	5	1.099	6	England	3	2.098	6
Australia	4	0.879	7	India	2	1.399	7
Japan	4	0.879	7	Thailand	2	1.399	7
Malaysia	4	0.879	7	Australia	1	0.699	9
Canada	3	0.659	10	Colombia	1	0.699	9
England	3	0.659	10	Germany	1	0.699	9
Spain	3	0.659	10	Indonesia	1	0.699	9
Ordan	2	0.44	13	Italy	1	0.699	9
Mexico	2	0.44	13	New Zealand	1	0.699	9
The Netherlands	2	0.44	13	Romania	1	0.699	9
Norway	2	0.44	13	Singapore	1	0.699	9
Serbia	2	0.44	13	South Korea	1	0.699	9
Lithuania	1	0.22	18				
New Zealand	1	0.22	18				
Saudi Arabia	1	0.22	18				
Singapore	1	0.22	18				
Sweden	1	0.22	18				

tries/territories where GRA and grey prediction studies were carried out were presented in Figs. 4 and 5, respectively. Taiwan with 225entries, (49.67%), China with 130 entries (28.7%), India with 58 entries (12.8), Turkey with 13 entries (2.87%), USA with 9 entries (1.77%) and South Korea with 5 entries (1.10%) are the top six countries/territories publishing GRA studies. Out of the 453 GRA studies, 355 (78.37%) were undertaken by corresponding authors in Taiwan or China. Further search on the ISI web-based software indicates that Singapore has one entry published in 1997. One

interesting finding was that not until the year of 2003, did we see GRA studies undertaken by authors outside Chinese societies be published in ISI Web of Knowledge indexed journals (Table 3).

With regard to grey prediction studies, the countries/territories of the corresponding authors is primarily Taiwan with 88 entries (61.54%), followed by China (38 entries; 26.57%), USA (5 entries; 3.5%), Japan/Turkey (4 entries; 2.80% each), and England (3 entries; 2.10%). The majority of grey prediction studies were conducted in Chinese societies. As shown in Table 3, out of the 143 grey prediction studies, 126 (88.11%) were originated in Taiwan or China. The geographic distribution of grey prediction studies over time shows that the earliest entry originated in countries/territories outside the Chinese context was from England in 2005. USA, Japan and Turkey simultaneously had their first entries in 2007. As can be seen in Figs. 4 and 5, the number of peer-reviewed articles per country/territory exhibited sustaining growth with minor fluctuations during the time period examined, indicating that GST research had been gradually flourished in the top six countries/territories. Publication frequencies, percentages and rankings of countries/territories

Table 4
Distributions of GRA studies by subject areas.

Subject areas	Record counts	% of total
Engineering	206	45.275
Mathematics	91	20.000
Computer Science	90	19.780
Materials Science	77	16.923
Automation Control Systems	53	11.648
Operations Research Management Science	52	11.429
Energy Fuels	17	3.736
Polymer Science	16	3.516
Business Economics	14	3.077
Physics	13	2.857
Environmental Sciences Ecology	11	2.418
Metallurgy Metallurgical Engineering	10	2.198
Optics	9	1.978
Construction Building Technology	7	1.538
Thermodynamics	7	1.538
Transportation	7	1.538
Water Resources	7	1.538
Mechanics	6	1.319
Telecommunications	6	1.319
Science Technology other Topics	5	1.099
Chemistry	4	0.879
Geology	4	0.879
Instruments Instrumentation	4	0.879
Acoustics	3	0.659
Biotechnology Applied Microbiology	3	0.659
Information Science Library Science	3	0.659
Oceanography	3	0.659
Agriculture	2	0.44
Mathematical Computational Biology	2	0.44
Neurosciences Neurology	2	0.44
Psychology	2	0.44

Table 5
Distributions of grey prediction studies by subject areas.

| Subject Areas	Records counts	% of total
Engineering	77	53.846
Computer Science	38	26.573
Automation Control Systems	23	16.084
Mathematics	23	16.084
Operations Research Management Science	19	13.287
Energy Fuels	14	9.790
Mechanics	9	6.294
Thermodynamics	9	6.294
Instruments Instrumentation	8	5.594
Environmental Sciences Ecology	5	3.497
Materials Science	5	3.497
Physics	5	3.497
Construction Building Technology	4	2.797
Metallurgy Metallurgical Engineering	4	2.797
Transportation	4	2.797
Business Economics	3	2.098
Science Technology other Topics	3	2.098
Plant Sciences	2	1.399
Telecommunications	2	1.399
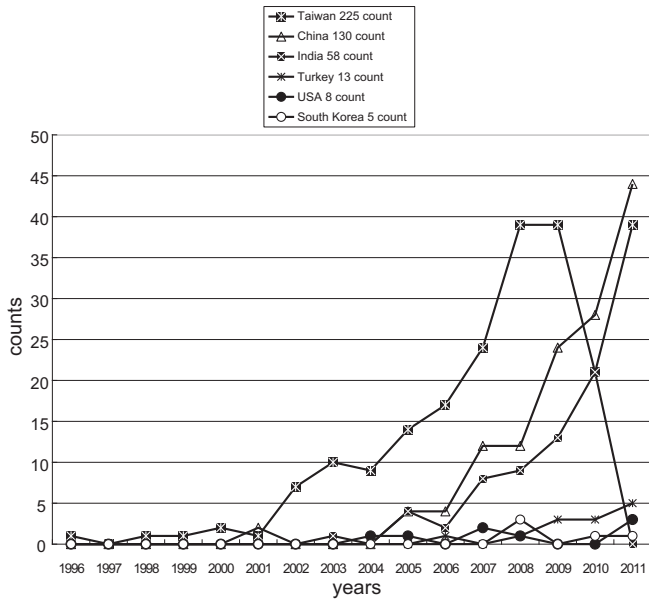
Fig. 6. Annual publication outputs of GRA articles by the top six productive countries/territories.
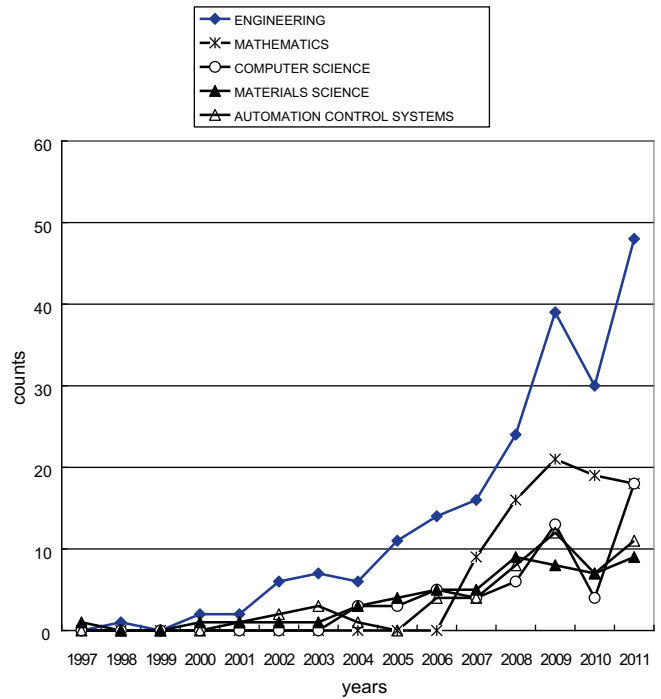

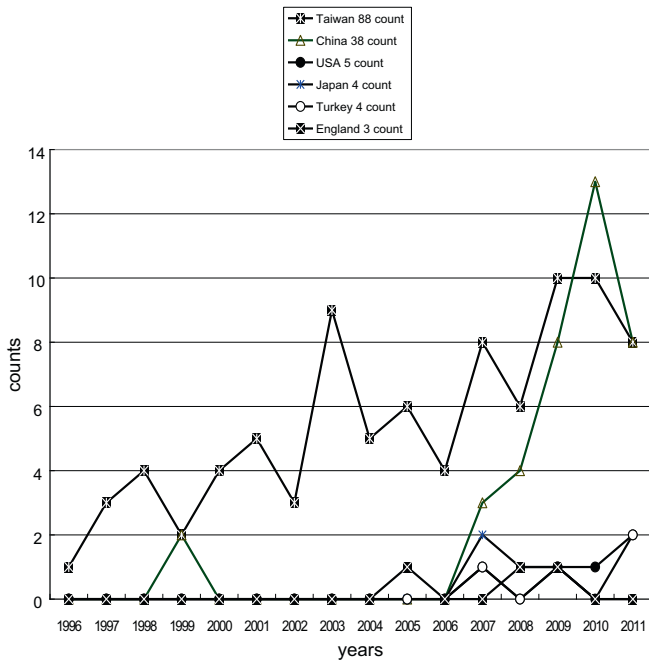**Fig. 8.** Annual publication outputs of GRA articles by the top five subject areas.

Fig. 7. Annual publication outputs of grey prediction articles by the top six productive countries/territories.
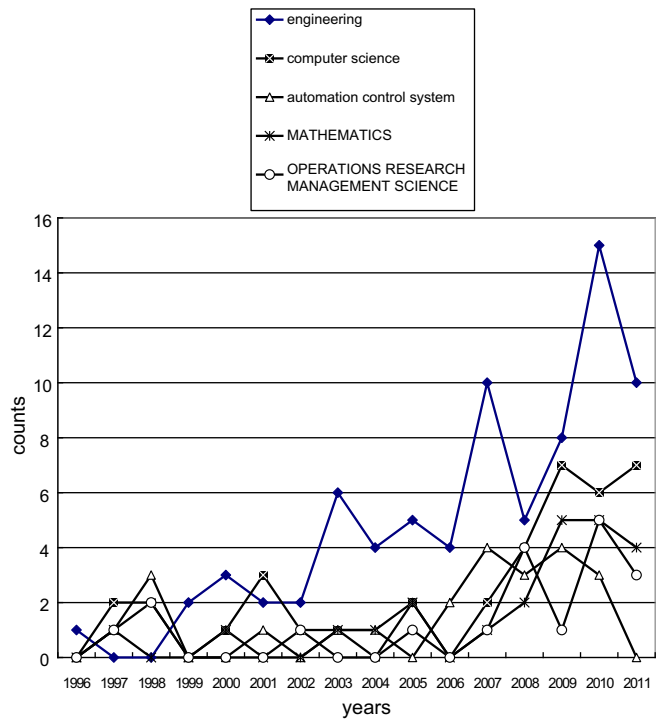

Fig. 9. Annual publication outputs of grey prediction articles by the top five subject areas.

where GST studies were conducted was presented in Table 5, indicating that a total of 17 countries/territories has contributed to grey prediction studies and a total of 22 has contributed to GRA studies.

4.3. Distribution of GRA and grey prediction studies by subject areas

For subject area analysis, 453 GRA studies and 143 grey prediction studies were analyzed statistically based on subject areas provided by ISI Web of Knowledge. Tables 4 and 5 show subject areas with a minimum of two entries. As can be seen in the tables, engi-

neering was the most common subject area for both GRA and grey prediction studies, followed distantly by other subject areas. In addition to engineering, mathematics, computer science, automation control system, operations research management science and energy fuel were among the most common subject areas found in studies employing GRA and grey prediction. The growth trends
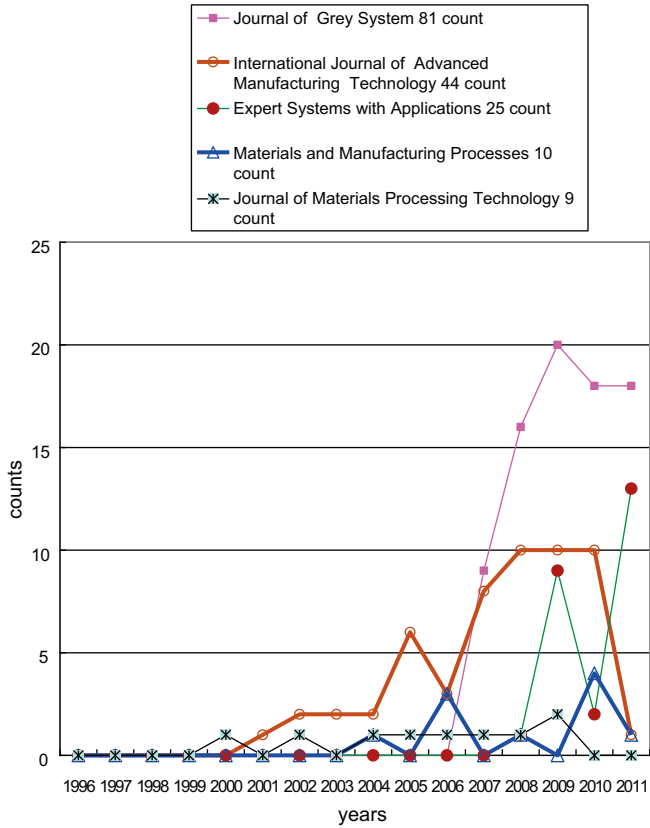
Fig. 10. Annual publication outputs of GRA articles by the top five productive source titles.
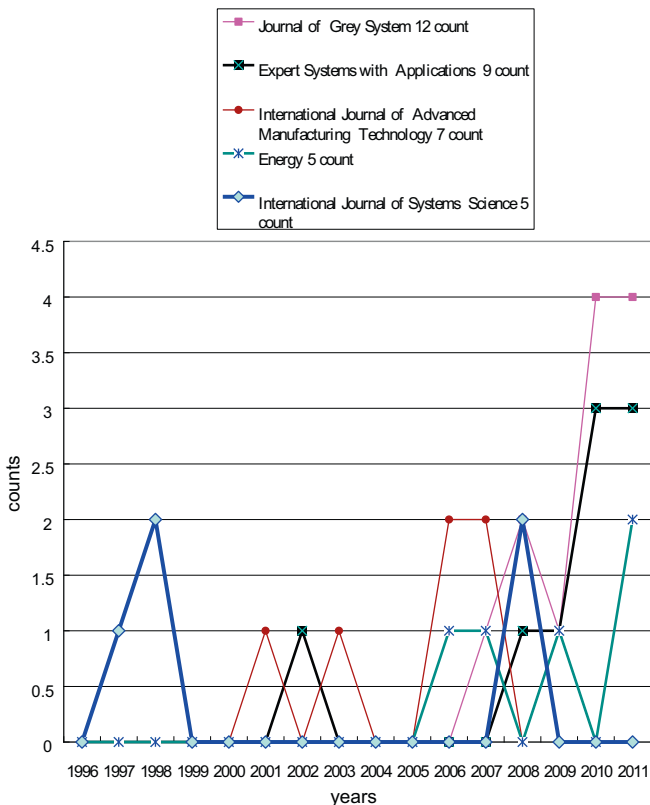

Fig. 11. Annual publication outputs of grey prediction articles by the top five productive source titles.

Table 6
The top 10 most productive source titles on GRA studies and impact factors.

Source titles	Records	% of 453	IF
Journal of Grey System	81	17.802	0.284
International Journal of Advanced Manufacturing Technology	44	9.67	1.103
Expert Systems with Applications	25	5.495	2.203
Materials and Manufacturing Processes	10	2.198	1.058
Journal of Materials Processing Technology	9	1.978	1.783
Journal of the Chinese Institute of Engineers	7	1.538	0.295
Journal of Reinforced Plastics and Composites	6	1.319	0.727
Materials & Design	6	1.319	2.200
Neurocomputing	5	1.099	1.580
Optics and Laser Technology	5	1.099	1.515

Table 7
The top 10 most productive source titles on grey prediction studies and impact factors.

Source titles	Records	% of 143	IF
Journal of Grey System	12	8.392	0.284
Expert Systems with Applications	9	6.294	2.203
International Journal of Advanced Manufacturing Technology	7	4.895	1.103
Energy	5	3.497	3.597
International Journal of Systems Science	5	3.497	0.991
Applied Energy	3	2.098	5.106
Applied Mathematics and Computation	3	2.098	1.317
Applied Mathematical Modelling	2	1.399	1.579
Building and Environment	2	1.399	2.400
Electric Power Components and Systems	2	1.399	0.349
Energy Conversion and Management	2	1.399	2.216
Fuzzy Sets and Systems	2	1.399	1.759
IEEE Transactions on Systems Man and Cybernetics Part C Applications and Reviews	2	1.399	2.009
International Journal of Heat and Mass Transfer	2	1.399	2.407
International Journal of Innovative Computing Information and Control	2	1.399	1.667
International Journal of Machine Tools Manufacture	2	1.399	1.919
Journal of Central South University of Technology	2	1.399	0.331

of the top five subject areas for GRA and grey prediction studies were plotted in Figs. 6 and 7, indicating the continuous increase in the number of articles per subject areas.

Of the 453 studies on GRA, the subject area of engineering contains 206 studies (45.28%), mathematics contains 91 studies (20%), computer science contains 90 studies (19.8%), materials science contains 77 (16.9%), automation control system was with 53 articles (11.7%), and operations research management science with 52 articles (11.4%). The remaining subject areas contain less than 20 entries. Of the 143 studies on grey prediction, the subject area of engineering contains 77 studies (53.8%), computer science contains 38 studies (26.6%), automation control system and mathematics were with 23 studies (16.1%), respectively, and automation control system contains 19 articles (13.3%). The remaining subject areas contain less than 15 entries (Table 5). Annual publication outputs of grey prediction and GRA articles by the top five subject areas are shown below in Figs. 8 and 9 below.

4.4. Distribution of GRA and grey prediction studies by source titles

In total, 453 GRA papers were published in 194 journals indexed in ISI Web of Knowledge. Annual publication output of GRA by the top five journals was presented in Fig. 10. *Journal of Grey System* has the most publications on GRA (81; 17.88%),

Table 8
The top 10 most cited articles on GRA.

Article title	Countries	PY	Source title	C	C/Y	JIF
The use of the orthogonal array with grey relational analysis to optimize the electrical discharge machining process with multiple performance characteristics	Taiwan	2002	International Journal of Machine Tools and Manufacture	88	8.00	1.919
The use of grey-based Taguchi methods to determine submerged arc welding process parameters in hardfacing	Taiwan	2002	Journal of Materials Processing Technology	68	6.18	1.783
The integration and application of fuzzy and grey modeling methods	Taiwan	1996	Fuzzy Sets and Systems	65	3.82	1.759
Optimisation of the EDM process based on the orthogonal array with fuzzy logic and grey relational analysis method	Taiwan	2002	International Journal of Advanced Manufacturing Technology	59	5.36	1.103
Reconfiguring the innovation policy portfolios for Taiwan's SIP Mall industry	Taiwan	2007	Technovation	57	9.50	3.287
Manufacturing process optimization for wear property of fiber-reinforced polybutylene terephthalate composites with grey relational analysis	Taiwan	2002	Wear	53	5.30	1.872
Multi-criteria material selections and end-of-life product strategy: Grey relational analysis approach	China	2007	Materials & Design	47	7.83	2.2
Form design of product image using grey relational analysis and neural network models	Australia	2006	Computers & Operations Research	44	5.50	1.72
Applying grey relational analysis and grey decision-making to evaluate the relationship between company attributes and its financial performance – A case study of venture capital enterprises in Taiwan	Taiwan	2007	Decision Support Systems	44	7.33	1.687
Application of grey relational analysis for corrosion failure of oil tubes	China	2001	Corrosion Science	41	3.42	3.374

followed by *International Journal of Advanced Manufacturing Technology* (44; 9.71%), *Expert Systems with Applications* (25; 5.52%), *Materials and Manufacturing Processes* (10; 2.21%), and *Journal of Materials Processing Technology* (9; 1.99%). As noted earlier, *Fuzzy Sets and Systems* was the first indentified journal indexed by ISI Web of Knowledge publishing a GRA paper in 1996. Of the 194 journals, 34 journals contain 2 entries (17.53%), and 135 journals contain 1 entry (69.58%). Twenty-five journals (12.89%) contain more than 3 entries.

From 1996 to 2011, a total of 143 grey prediction papers were published in 89 journals indexed in ISI Web of Knowledge. Annual publication outputs of grey prediction articles by the top five productive was presented in Fig. 11. Among these, *Journal of Grey System* ranks the first with 12 entries on grey prediction (8.39%), followed by *Expert Systems with Applications* (6; 6.29%), *International Journal of Advanced Manufacturing Technology* (7; 4.90%), *Energy* and *International Journal of Systems Science* ((5; 3.50% each). As noted earlier, *International Journal of Machine Tools and Manufacture* was the first indentified journal indexed by ISI Web of Knowledge publishing a grey prediction paper in 1996. Of the 89 journals, 17 journals contain 2 entries (19.10%), and 65 journals contain only 1 entry (73.03%). Seven journals (7.86%) contain more than 3 entries.

The most widely method used to measure a journal's relative influence is the impact factors reported by the 2011 edition of *Journal Citation Reports* (JCR). The impact factors (IF) of the top 10 most productive source titles on GRA and grey prediction studies are displayed in Tables 6 and 7. Of the 194 journals publishing GRA studies, *Expert Systems with Applications* ranked first in IF (2.203), followed by *Materials Design* (2.200), *Journal of Materials Processing* (1.783), *Neurocomputing* (1.580), and *Optics and Laser Technology* (1.515). Of the 89 journals publishing grey prediction studies, *Applied Energy* ranked the first in IF (5.106), followed by *Energy* (3.597), *International Journal of Heat and Mass Transfer* (2.407), *Building and Environment* (2.400), and *Expert Systems with Applications* (2.203).

5. Citation frequency

The top 10 most frequently cited GRA articles for the years 1996 through 2011 are presented in Table 8 below. Seven of the most frequently cited articles were originated in Taiwan, 2 in China and 1 in Australia. Of the 10 source titles which published the top 10 most cited GRA articles, *Corrosion Science* was with the highest impact factor (3.374), followed by *Technovation* (3.287), *International Journal of Machine Tools & Manufacture* (1.919), and *Materials & Design* (2.200).

A summary of the top 10 most frequently cited grey prediction papers reveals that seven of the most frequently cited articles were originated in Taiwan, 2 in China and 1 in Turkey. Table 9 shows

Table 9
The top 10 most cited articles on grey prediction.

| Title	Countries	PY	Source title	C	C/Y	JIF
Control of an inverted pendulum using grey prediction model	Taiwan	2000	IEEE Transactions on Industry Applications	80	6.15	1.657
Predicting stock price using fuzzy grey prediction system	Taiwan	2002	Expert Systems with Applications	78	7.09	2.203
Applications of improved grey prediction model for power demand forecasting	Taiwan	2003	Energy Conversion and Management	75	7.50	2.216
Applying the grey prediction model to the global integrated circuit industry	Taiwan	2003	Technological Forecasting and Social Change	65	6.50	1.107
Grey prediction with rolling mechanism for electricity demand forecasting of Turkey	Turkey	2007	Energy	54	9.00	3.597
Real-valued genetic algorithms for fuzzy grey prediction system	Taiwan	1997	Fuzzy Sets and Systems	50	3.12	1.759
Improved grey prediction models for the trans-Pacific air passenger market	Taiwan	1998	Transportation Planning and Technology	49	3.27	0.203
Form design of product image using grey relational analysis and neural network models	Australia	2005	Computers & Operations Research	44	5.50	1.72
A trigonometric grey prediction approach to forecasting electricity demand	Singapore	2006	Energy	42	6.00	3.487
The gray prediction search algorithm for block motion estimation	Taiwan	1999	IEEE Transactions on Circuits and Systems for Video Technology	32	2.29	1.649
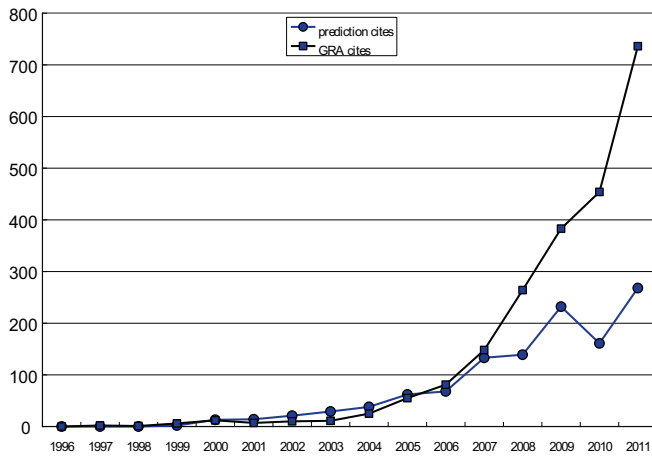
Fig. 12. Annual outputs of total numbers of GRA and grey prediction citations.

that of the source titles which published the top 10 most cited articles on grey prediction, *Energy* is had the highest impact factor (3.597), followed by *Energy Conversion and Management* (2.216) and *Expert Systems with Applications* (2.203). Distributions of the most cited GRA and grey prediction articles by publication years are presented in Fig. 12. The number of citations for GRA and grey prediction articles per year tends to increase substantially with years, indicating the two models derived from grey system theory have been gradually accepted as novel research directions.

6. Discussion and conclusions

An attempt has been made in this bibliometric study to offer an effective way to build on existing research in the field of grey system theory. This paper highlights the applications areas of the following two widely applied models: grey relational analysis and grey prediction. Results of the study demonstrate that there has been a substantial increase in the number of peer-reviewed papers in GRA or grey prediction published in journals indexed by the ISI Web of Knowledge. Both GRA and grey prediction studies were published in a broad range of source titles, with over 400 journals being represented in GRA studies and 100 journals in grey prediction studies.

The results brings out an interesting observation that in the earlier phase of such investigations, GRA, as a developed multiple attribute decision-making tool, has been predominantly studied in Taiwan and China. Taiwan is evident the torchbearer in this field in both publication and citation analyses. It gradually received international recognition after the year of 2003. The progression of GRA and grey prediction studies was investigated via citation patterns within the different source titles. The present study also provides lists of core source titles containing GRA and grey prediction studies in order to serve as a journal-wise search for those who wish to have their papers in various application areas published in journals indexed by the ISI Web of Knowledge software.

There are a number of limitations to this study. First, the present study included only one document type, peer-reviewed articles, which represent only a portion of literature published within the field of GST. Future bibliometric studies on the progression of GST may extend the present study by investigating conference proceeding papers, book chapters, or other document types of GST studies. The database of *Engineering Village* would be another source of scholarship being reviewed to further trace the rise and fall of wider applications in GST literature. Moreover, this study only examined two widely applied GST models; it would be more productive to conduct meta-analytic reviews of literature on the combination of GRA or grey prediction with other techniques in various areas of applications. For example, fuzzification techniques were combined with grey prediction model to forecast stock price trends, power demands, etc. (Hsiao, Huang, & Chang, 2011; Wang, 2001). The merits of principal component analysis and GRA were integrated in a study evaluating the financial performance of several comparative companies, improving various facets of manufacturing process (Lu, Chang, Hwanga, & Chung, 2009; Tung, Lee, & Wang, 2009). Further synthesized reviews may also carried out to examine research efforts spent to improve and refine GM (1,1) model, such as F-GM(1,1) and T-GM(1,1) (Li, Yamaguchi, Nagai, & Mascuda, 2008; Tien, 2009). This would help identify areas in which GST research might be able to make significant contributions in the future. Finally, the current study adopted number of citations and JCR's impact factor to measure the influence of journals publishing GST articles. H-index, journal rank, average number of citations per publications, or other indicators of publication quality may be used in follow-on studies to further quantify the scientific merits of GST literature (Hirsch, 2005; Li & Ho, 2008). As the above issues and limitations are addressed, it would be certain that grey system theory will continue to innovate and expend to a wider range of possibilities.

References

Deng, J. L. (1989). An introduction to grey system theory. *Journal of Grey System, 1*, 1–24.

Hirsch, J. E. (2005). An index to quantify an individual's scientific research output. *Physics, 102*, 16569–16572.

Ho, Y. S. (2008). Bibliometric analysis of biosorption technology in water treatment research from 1991 to 2004. *International Journal of Environmental Pollution, 33*, 1–13.

Hsiao, Y. T., Huang, T. L., & Chang, S. Y. (2011). Fuzzy modeling with grey prediction for designing power system stabilizers. *Granular Computing and Intelligence Systems, 13*, 219–235.

Li, G. D., Yamaguchi, D., Nagai, M., & Mascuda, S. (2008). The prediction of asphalt pavement permanent deformation by T-GM(1,2) dynamic model. *International Journal of Systems Science, 39*, 959–967.

Li, Z., & Ho, Y. S. (2008). Use of citation per publication as an indicator to evaluate contingent valuation research. *Scientometrics, 75*, 97–110.

Liu, S. F., & Lin, Y. (1998). *An introduction to grey systems*. PA, USA: IIGSS Academic Publisher.

Liu, S. F., & Forrest, J. (2007). The current development status on grey system theory. *Journal of Grey System, 19*, 111–123.

Lin, Y., & Liu, S (2004). A historical introduction to grey system theory. *A paper presented at Systems*, Man and Cybernetics 2004 IEEE International Conference.

Lindsey, D. (1980). Production and citation measures in the sociology of science: The problem of multiple authorship. *Social Studies of Science, 10*, 145–162.

Lu, H. S., Chang, C. K., Hwanga, N. C., & Chung, C. T. (2009). Grey relational analysis coupled with principal component analysis for optimization design of the cutting parameters in high speed end milling. *Journal of Materials Processing Technology, 209*, 3808–3817.

Osareh, F. (1996). Bibliometrics, citation analysis and co-citation analysis: A review of literature. *Libri, 46*, 149–158.

Tien, T. L. (2009). A new grey prediction model FGM(1, 1). *Mathematical and Computer Modelling, 49*, 1416–1426.

Tung, C. T., Lee, Y. J., & Wang, K. H. (2009). Combining grey theory and principal component analysis to evaluate financial performance of airline companies in Taiwan. *Journal of Grey System, 21*, 357–368.

Wang, Y. F. (2001). Predicting stock price using fuzzy grey prediction system. *Expert Systems with Applications, 22*, 33–38.

Wang, Q. Y. (2000). Uncertainty information and uncertainty systems. *Kybernetes, 29*, 1223–1230.

Wen, K. L., Chao, J. S., Chang, H. J., Chen, H. Y., & Wen, H. C. (2009). *Grey system theory and applications*. Taiwan: Wunan Publisher.