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Invited Review

Quantitative models for managing supply chain risks: A review

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A B S T R A C T

As supply chain risk management has transitioned from an emerging topic to a growing research area, there is a need to classify different types of research and examine the general trends of this research area. This helps identify fertile research streams with great potential for further examination. This paper presents a systematic review of the quantitative and analytical models (i.e. mathematical, optimization and simulation modeling efforts) for managing supply chain risks. We use bibliometric and network analysis tools to generate insights that have not been captured in the previous reviews on the topic. In particular, we complete a *systemic mapping* of the literature that identifies the key research clusters/topics, interrelationships, and generative research areas that have provided the field with the foundational knowledge, concepts, theories, tools, and techniques. Some of our findings include (1) quantitative analysis of supply chain risk is expanding rapidly; (2) European journals are the more popular research outlets for the dissemination of the knowledge developed by researchers in United States and Asia; and (3) sustainability risk analysis is an emerging and fast evolving research topic.

1. Introduction to supply chain risk management

Global supply chains are becoming more complex and hence more vulnerable to disruptions with large unanticipated consequences of seemingly contained events (Craighead et al., 2007). Numerous examples of severe supply chain disruptions exist. The September 11 attacks in 2001, the Tohoku earthquake and tsunami, and the Thai flood in 2011 have resulted in severe supply chain disruptions. We have also witnessed over the last decade numerous product recalls (e.g. toys (Mattel), pet foods (Menu), and drugs (Baxter)) caused by less responsible international suppliers. In addition to legal liabilities, supply chain disruptions can also have long-term stock price effects and equity risk effects (Hendricks & Singhal, 2005). In most instances, such disruptions are either due to natural risks (e.g. earthquake, floods, fire, and tsunami) or man-made risks (e.g. terrorist attacks, accidents, supplier adulterations, and cyber-attacks) that are inherent to the underlying global supply chains (Heckmann et al., 2015; Jabbarzadeh et al., 2014). While certain supply chain risks can be prevented, other risks can be mitigated so that supply chain operations can be restored quickly after a disruption. Some of the more common strategies for mitigating supply chain risks include managing vulnerabilities through *Agility* (Lee, 2004), *Flexibility* (Tang & Tomlin, 2008), and *Resilience* (Sheffi & Rice, 2005).

In addition to major disruptions, supply chains also face interruptions caused by several sources of inherent uncertainties such as demand fluctuations, supply capacity changes, lead time variability, and exchange rate volatility (Esmaeilikia et al., 2014a). While many supply chain executives are reporting increased concerns about the rise of disruption and interruption risks (Chopra & Sodhi, 2004; Sheffi, 2005; Sodhi & Tang, 2012), few companies have taken commensurate actions to manage these risks effectively (McKinsey, 2006). This gap makes supply chain risk management (SCRM) an attractive research area. As researchers further engage in this emergent research topic, a natural first step is to define and classify supply chain risks (see for example Esmaeilikia et al. 2014b; Jüttner et al. 2003; Sodhi & Tang 2010). Concurrently, there is a need to construct frameworks to help make sense of the field. One framework development tactic is to classify works using an evolutionary perspective such as: (1) identifying risks; (2) assessing risks; (3) mitigating risks; and (4) responding to risks (e.g. see Blackhurst & Wu 2009; Sodhi & Tang 2010; Zsidisin & Ritchie 2010).[1]

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[1] We also refer the reader to www.husdal.com for comprehensive reviews, blogs, and comments about books and articles related to SCRM.

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0377-2217/

SCRM is a multi-disciplinary area with research and practice that draws on supply chain management, enterprise risk management (which includes supply risks), business continuity (which includes supply sustainability risks), and crisis management (Sodhi & Tang, 2012). These domains draw on a broad swathe of the academic literature in disciplines such as organizational behavior, psychology, decision analysis, empirical analysis, and mathematical and stochastic modeling. This far-reaching and multi-disciplinary nature of SCRM research can make it overwhelming for researchers to explore research opportunities in this field. While many highly cited articles are available on a range of topics, understating whether or not a particular SCRM topic has been well studied remains a challenge.

In order to synthesize various SCRM research articles, some recent studies have provided thorough reviews focusing on the broader field (Tang, 2006; Tang & Nurmaya Musa, 2011), while others have focused on specific aspects such as robust supply chain design (Klibi et al., 2010), flexible supply chain planning (Esmaeilikia et al., 2014b), or partner selection risks (Wu & Barnes, 2011). In an effort to identify more objective and nuanced SCRM research, a methodological and analytical approach is used in this paper to examine a focused portion of this literature, providing additional and greater insight into past, current and future research.

As articulated in Sodhi, Son and Tang (2012), it is fundamentally difficult to classify SCRM research because different researchers used different definitions, interpretations and synonyms to explain SCRM and related concepts from different perspectives. Early definitions for SCRM included generalities such as the variation in the distribution of possible supply chain outcomes, their likelihood, and their subjective values (March & Shapira, 1987). Other definitions were more specific to certain characteristics, such as the possibility and effect of mismatch between supply and demand (Jüttner et al., 2003). There have been efforts to extend this definition to situations that present a risk to information, material and product flows from suppliers to final product delivery to the ultimate end-user (Peck, 2006). We adopt the latter general definition in this paper because it concurs with the philosophy that SCRM is typically considered as a pure event-oriented concept with two common components of probability of occurrence and related consequences (Heckmann et al., 2015). Selecting an appropriate definition is critical to identifying keywords for the literature search. This is why clear foundation definition, although difficult to identify, is needed and variations in selected definitions may result in search result variations. The broader SCRM terms and definitions used in this study are informed and supported by Esmaeilikia et al. (2014b), Heckmann et al. (2015), Peck (2006) and Zsidisin (2003).

SCRM research can adopt different research methods and data collection approaches to investigate the related issues. In general, most approaches can fit into either positive or normative research methods (Jüttner et al., 2003). *Positive research* methods attempt to describe, explain, predict and understand the SCRM activities that are currently practiced or were practiced in the past. Most qualitative research methods such as in-depth interviews, laboratory experiments, and empirical case studies as well as quantitative surveys fit into this class of research methods. In contrast, *normative research* tends to prescribe what organizations and individuals should do to better manage supply chain risks. Most of the quantitative and modeling studies fit into the latter category. Our aim in this paper is to provide a comprehensive review on quantitative SCRM modeling efforts. Although many seminal papers on the positive research side have contributed to this field, such as concept building practical papers published in professionally-oriented management journals and empirical works published in management oriented journals, the primary focus in our review is on papers that have formal modeling methodologies and techniques as their primary underlying purpose. Formal modeling is an important research area since their normative and prescriptive nature can prove extremely beneficial for developing decision making tools and support systems. These approaches have significant practical and managerial insight that can help organizations maintain or create competitive advantage. A focus on this area is therefore of both practical and theoretical importance.

The primary focus and contributions of this paper include the following. First, we review over 1000 SCRM quantitative and formal modeling papers. We present a systematic literature review that differs from standard reviews in that it employs a replicable, scientific and transparent structured process to reduce bias in the selection of studies and to summarize them objectively. Second, rigorous bibliometric and network analysis tools are used to work with complex data sets and investigate large citation and co-citation networks, something that has never been examined in this field. Third, our literature mapping and data clustering result in innovative topical classification of the works allowing us to identify the mature and emergent research streams. Forth, a second network analysis and data clustering is completed to classify the generative studies that have provided the field with the foundational knowledge, concepts, theories, tools, and techniques.

The remainder of this paper is organized as follows. In Section 2, we discuss our research methodology along with some summary statistics regarding recent trend in the output of quantitative SCRM research. Section 3 presents our initial bibliometric analysis resulting in additional author and affiliation statistics. In Section 4, we present a thorough network analysis including a citation and a co-citation network analysis that eventually results in identifying key clusters of primary research streams and generative research areas. We conclude this paper in Section 5 with a discussion on research limitations and potential research directions.

2. Research methodology and initial data statistics

Literature reviews aim to map and evaluate the body of literature and identify potential research gaps highlighting the boundaries of knowledge (Tranfield et al., 2003). Systematic literature reviews are completed through an iterative process of defining appropriate search keywords, searching the literature and completing the analysis (Saunders et al., 2009). Systematic reviews differ from traditional narrative reviews in that they employ a replicable, scientific and transparent process that minimizes the selection bias through exhaustive literature search (Petticrew & Roberts, 2006; Tranfield et al., 2003). In particular, systematic literature reviews aim to reduce bias in the selection of studies and to summarize them objectively (Petticrew & Roberts, 2006). Rowley and Slack (2004) recommend a structured methodology for scanning resources, designing the mind map to structure the literature review, writing the study, and building the bibliography. Similarly, we use a four-step methodology for data collection and comprehensive evaluation of the field aiming to identify the most influential studies, determine the topical areas of current research interest and provide insights for current research interests and directions for future research in the field.

1. *Defining the appropriate search terms:* We design a three-level keyword assembly structure that aims to accommodate a broad range of search terms for capturing published robust and flexible supply chain models. Table 1 shows the assembly structure where level one defines the search context (supply chain), level 2 outlines risk and uncertainty keywords, and level 3 contains the related modeling keywords. The proposed structure was obtained through defining the popular risk keywords at level 2 from previous literature reviews on the topic, and a set of relevant modeling keywords at level 3. The modeling keywords are kept at a general level to cover a broader range of studies. For example, “heuristics” and “meta-heuristics” are used instead of specific

Table 1
The proposed three-level keyword assembly structure.

Context keyword: supply chain
AND
Risk/uncertainty keywords: risk OR uncertain OR uncertainty OR flexible OR flexibility OR robust OR robustness OR agile OR agility OR resilient OR resiliency OR resilience OR vulnerable OR vulnerability OR disruption OR interruption OR variation OR volatile OR volatility OR fluctuate OR fluctuation
AND
Modeling keywords: optimization OR optimization OR (mathematical model) OR (numerical model) OR (numerical method) OR (decision tool) OR (decision model) OR (decision analysis) OR simulation OR (discrete event) OR heuristics OR meta-heuristic OR metaheuristic OR stochastic OR probabilistic OR (linear programming) OR (nonlinear programming) OR (integer programming) OR (mathematical programming) OR (dynamic programming) OR MILP OR MINLP OR multi-objective OR multiobjective OR multi-attribute OR multi attribute OR (multiple criteria decision making) OR (multi-criteria decision making) OR MCDM OR (multiple criteria decision analysis) OR (multi-criteria decision analysis) OR MCDA

Table 2
The top 10 subject areas.

Subject area	No. of papers
Engineering	530
Decision sciences	473
Business, management and accounting	361
Computer science	300
Mathematics	176
Economics, econometrics and finance	93
Social sciences	76
Environmental science	74
Chemical engineering	59
Agricultural and biological sciences	47

methods and algorithms such as "Genetic Algorithm" or "Simulated Annealing".

2. *Initial search results*: Using the "title, abstract, keywords" search in the Scopus database,[2] articles with the keywords identified in Table 1 were collected and stored. The initial search attempts resulted in a total of 2304 papers. We further limited the search space to 'journal' papers written in English and excluded conference papers, book series, commercial publications and magazine articles. This reduced the raw data set to 1108 papers which will serve as the primary data source for the literature analysis. The top 10 subject areas (disciplinary fields) contributing to this database are shown in Table 2. A paper may be listed in more than one subject area depending on the identified contribution areas by Scopus. The search results were stored in RIS format to include all the essential paper information such as paper title, authors' names and affiliations, abstract, keywords and references.
3. *Initial data statistics:* Fig. 1 shows the publishing trend in the field by plotting the quantity of publications from the years 1978 to 2013 (the earliest year for a publication meeting our search criteria in the database was found to be 1978). A geometric growth in the number of publications can be observed especially after 1997. The only downward trend in the 2009/2010 interval is made up immediately by the significant rise in the number of publications in the 2010/2011 interval. The initial statistics also show that 396 journals have contributed to the publication of those 1108 papers. The top 10 journals have published 358 of these articles, representing approximately 32 percent of all the published papers. Table 3 shows the contribution of journals in which at least 10 of the identified SCRM modeling papers have appeared.
4. *Data analysis:* Given the nature of a citation analysis study, we adopt an inductive approach for the purpose of data analysis (Seuring & Müller, 2008). The literature classification portion is completed before the actual data analysis using a deductive approach. Data analysis is conducted in two parts including 'bibliometric analysis' and 'network analysis'. Bibliometric analysis provides additional data statistics including author, affiliation and keyword statistics. We use BibExcel because of its capability to handle large data sets and its compatibility with different computer applications including Excel, Pajek and Gephi (Persson et al., 2009). BibExcel is also used to prepare the input data for a detailed network analysis. The network analysis part uses a tool called Gephi to perform citation analysis, co-citation analysis, and the topical content-based classification of the existing SCRM modeling efforts. Gephi is chosen over other existing network analysis software such as Pajek (Batagelj & Mrvar, 2011) and VOSviewer (van Eck & Waltman, 2013) due to its capability to work efficiently with large data sets, and its flexibility to develop a wide range of innovative analysis and investigation options.

3. Bibliometric analysis

This section presents the initial author and affiliation statistics obtained from our initial bibliometric analysis. Identifying the key researchers and universities in different geographical regions can be helpful for scholars and students who are interested in conducting SCRM research with researchers at various universities. BibExcel is used to perform the initial bibliometric and statistical analyses and to prepare the raw data for additional network analysis in Section 4. BibExcel is a tool for analyzing bibliographic data or any data of a textual nature formatted in a similar manner (Persson et al., 2009). BibExcel allows modifying and/or adjusting data that can be imported from various databases including Scopus and Web of Science. The data output can be exported to Excel or any program that takes tabbed data records. This high degree of flexibility makes BibExcel a powerful tool, yet relatively difficult to work with especially in performing the initial setups.

RIS format, Scopus output, is used as input for BibExcel. The data contain publication bibliographic information. The analysis in this study focuses on the following data fields: authors, title, journal, publication year, keywords, abstract, affiliations, and references. These analyses require reformatting of the RIS file into a number of different formats, resulting in several file types. Interested readers can refer to Paloviita (2009) and Persson et al. (2009) for more detailed procedure and applications of BibExcel in bibliometric and statistical analyses.

3.1. Author influence

The author field was extracted from the data file and frequency of appearance of all authors associated with those 1108 articles was recorded. Only 20 percent of 2239 contributing authors have contributed to more than one paper, leaving 1797 authors appearing in only a single paper. Table 4 outlines key contributing authors based

[2] Managed by Elsevier publishing, Scopus is the largest abstract and citation database of peer-reviewed research literature in the fields of science, technology, medicine, social sciences, and arts and humanities. It covers over 20,000 peer-reviewed journals including those published by Elsevier, Emerald, Informs, Taylor and Francis, Springer and Inderscience. The Scopus coverage details including access to tens of millions of peer reviewed journal articles can be found at http://www.info.sciverse.com/scopus/scopus-in-detail/facts. The Scopus database is more comprehensive than Web-of-Science database which would include only ISI indexed journals, limited to 12,000 titles only (Yong-Hak, 2013). Since we are focusing on peer-reviewed journals, we found that the Scopus database would capture the most reputable international journals, some of which may be relatively new, but influential. Scopus has been used and recommended as a good source of supply chain peer reviewed articles (Chicksand et al., 2012). One limitation of Scopus is the limited access to pre-1996 peer reviewed journal articles.

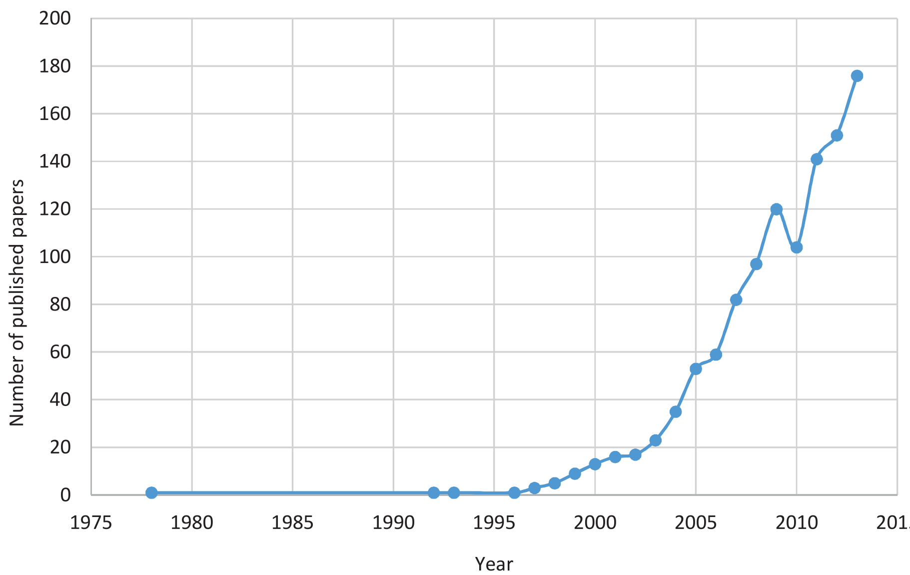

Fig. 1. Publishing trend in the area of supply chain risk modeling.

Table 3
Top journals contributing to the area of supply chain risk modeling.

Journal	Publication year																			
	1978	1993	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
International Journal of Production Research							1	3	2	2	3	2	4	6	7	10	11	10	16	77
International Journal of Production Economics					1	1	2		1	4		5	3	4	13	7	14	12	3	70
European Journal of Operational Research				1	2		1	2	1	3	1	6	8	4	7	8	7	3	8	62
Expert Systems with Applications														2	8	8	6	3	1	28
Computers and Industrial Engineering	1							1		1		5		5	3	3	1	2	3	25
Production Planning and Control									1		2		4	3	3	1	3	2	4	23
International Journal of Advanced Manufacturing Technology									1	1	3	2	1	1	1		2	3	7	22
Computers and Chemical Engineering						1				1			3	7	2		1	3	3	21
Industrial and Engineering Chemistry Research						2	1			1	2	3		2	2	2			1	16
Management Science			1		2				1	2	4		2				1	1		14
Production and Operations Management								2			1	1			1	2	2	1	3	13
Journal of the Operational Research Society		1			1	1	2			1	1	1	1	1		1	1	1		13
Omega						1					1	1	1	1	5		1			11
Manufacturing and Service Operations Management										1	1	2	1	1		1	3		1	11
Decision Support Systems															2	2	1	6		11
Computers and Operations Research							1	1	1					1	2	2	1	1	1	11
Annals of Operations Research											3		1				1		6	11
IIE Transactions (Institute of Industrial Engineers)							1	2			2		1	1	1	1	1			10
Operations Research						1			2	1			1		1		2	2		10
Naval Research Logistics							1		1	1		2	2	1			1		1	10
Journal of Manufacturing Technology Management											2	3		1		1	2		1	10
International Journal of Logistics Systems and Management												1		1	2	1	2	3		10
Total	1	1	1	1	6	7	10	11	11	19	26	34	33	42	60	50	64	53	59	489

on the number of published articles. We also completed an analysis to identify key paired-authors (i.e. those collaborating on multiple papers). Table 5 shows the paired-author results. Only two authors (Wu D. and Chan F.) appear in both tables. This result may demonstrate the need for more active scholars to collaborate with authors from different institutions, countries and disciplines in investigating SCRM problems, challenges and barriers from different angles.

We realize that author statistics may not be an effective approach to evaluate the contributions of each author, but it is one indicator to show the quantity of papers contributed. We will see in Section 4 that many of these authors have also co-authored the highly-influential papers in the field, indicating a positive relationship between the quantity and quality of papers published by the key contributing authors.

Fig. 2. Geographical locations of all contributing organizations. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

Table 4
Key contributing authors.

Author	No. of published articles	Author	No. of published articles
Chan F.	16	Wu D.	9
Shankar R.	14	Puigjaner L.	9
Chen Y.	13	Wu Y.	9
Chen C.	12	Xu X.	9
Tiwari M.	10	Zhao L.	9
Cruz J.	10	Zhang J.	9
Kumar S.	10		

Table 5
Key contributing paired authors.

Author 1	Author 2	Number of joint publications
Wu D.	Olson D.	7
Espuña A.	Puigjaner L.	7
Mele F.	Espuña A.	5
Mele F.	Puigjaner L.	5
Jain V.	Deshmukh S.	4
Guillén G.	Espuña A.	4
Guillén G.	Puigjaner L.	4
Adhitya A.	Srinivasan R.	4
Chan F.	Chung S.	4
Peidro D.	Mula J.	4

3.2. *Affiliation statistics*

The affiliations of the authors were extracted from the RIS file in BibExcel. For each affiliation, the city where the organization is located was obtained. Using the coordinates of these cities using gpsvisualizer.com, Fig. 2 shows the geographical locations of organizational affiliations contributing to the literature. The size of the red circles is proportional to the contribution degree of each organization. Greater density of contributing organizations can be found in the Middle-East (Iran in particular), the Eastern United States and the Western Europe. The figure also provides a summary of the number of papers published by the top contributing countries.

Table 6
Top contributing organizations.

Organization	Country	No. of papers
University of Tehran	Iran	19
Purdue University	United States	16
Indian Institute of Technology	India	15
Southeast University	China	14
Indian Institute of Technology Delhi	India	14
National University of Singapore	Singapore	13
Amirkabir University of Technology	Iran	13
Iran University of Science and Technology	Iran	12
Huazhong University of Science and Technology	China	12
Hong Kong Polytechnic University	Hong Kong	12
University of Connecticut	United States	11
City University of Hong Kong	Hong Kong	11
Islamic Azad University	Iran	10
Sharif University of Technology	Iran	10
Pennsylvania State University	United States	10
Carnegie Mellon University	United States	10
University of Michigan	United States	9
University of Toronto	Canada	9
Hsiuping Institute of Technology	Taiwan	9
Stanford University	United States	9

The top contributing organizations, their geographical locations and the quantity of published papers are shown in Table 6. The geographical dispersion of these organizations demonstrates that supply chain risk and uncertainty modeling has attracted organizations and research centers from around the globe. Surprisingly, none of the top 20 organizations in Table 6 are located in Europe. This result may be due to that researchers in many European schools tend to have more emphasis on empirical analysis, case study, field study, or broad-based surveys.

Another organizational level analysis can be completed on national and international collaborations between authors from different organizations. The results are shown in Tables 7 (national collaborations statistics) and 8 (international collaborations statistics). Obviously, single-author papers are not counted in this analysis. Table 7 shows that the United States has the highest national

Table 7
National collaboration statistics.

Country	No. of papers	Country	No. of papers
United States	163	United Kingdom	17
China	61	France	16
India	43	Canada	16
Taiwan	30	Netherlands	14
Iran	27	South Korea	12

collaboration rate. The U.S. is also the most active internationally, as one partner for 15 of the top 20 international collaborations (see Table 8). Another observation from Tables 6 to 8 is the significant contributions of developing countries such as China, Iran, India, Hong Kong and Taiwan, being active both nationally and internationally. These results may be due to where authors received their terminal (Ph.D.) degrees. It may be that collaborators with the U.S. received their doctoral degrees from U.S. schools. In addition, collaborators from English speaking countries (especially the U.K. and the U.S.) may be more sought out for publication in English language journals. Both these are conjectures at this time and additional research would be needed to determine the veracity of these initial suppositions.

4. Network analysis and literature mapping

A network analysis and graphical investigation is now completed for the selected sample. "Gephi" is used for this purpose, an open source software package for graph and network analysis. It uses a 3D render engine to develop illustrations of large networks in real-time and assist in speeding up the exploration process (Gephi, 2013). The flexible and multi-task architecture allows innovative approaches to work with complex data sets and produce insightful visual aids. Gephi provides easy and broad access to network data and assist in specializing, filtering, navigating, manipulating and clustering of data (Bastian et al., 2009).

For Gephi to map and visualize the citations among papers, a graph dataset is needed to be generated in which published papers are shown as nodes and citations are represented by the arcs/edges between the nodes. The bibliographic data obtained from Scopus (in RIS format) cannot be directly used for this purpose. The file needs to be reformatted to represent a graph dataset. BibExcel is used as a mediator to complete this task. Gephi accepts a number of graph data formats including '.NET' that BibExcel is able to generate. The RIS file contains different fields of information for each paper (e.g. the list of references and list of authors).

4.1. Citation analysis

Different methods have been used in the past to measure the significance of a publication. The most common method is a citation analysis which aims to determine the '*popularity*' of a publication by counting the number of times a publication is cited by other publications (Cronin & Ding, 2011). A citation analysis for the 1108 papers identified in Section 2 revealed that 605 papers have cited other in this 1108-node network. Table 9 shows the top 10 papers based on their number of citations.

A local citation analysis shows how many times a paper has been cited by others within this 1108-node network; while a global citation analysis provides the overall number of citations in Scopus, which includes citations from other disciplines and research areas. The noticeable mismatch between local citation and global citation values shows that risk modeling has also been an active research area in a range of other disciplines not captured in this study's search attempts. But the degree of attractiveness may vary from one paper to another based on type and quality of contributions. This finding is evidenced by the fact that the order of papers based on their local citation does not follow the global citation order. For example, Cachon and Lariviere (2005) is ranked sixth based on the number of local citations, not the most attractive locally; however, it has the highest number of global citations. In general, it takes time for a paper to establish citations; accordingly, a majority of the highly-cited papers in Table 9 are more than a decade old.

4.2. PageRank analysis

Besides citations, Ding, Yan, Frazho and Caverlee (2009) argue that "prestige" is another important indicator of impact. Prestige can be measured as the number of times a paper is cited by other highly cited papers. A highly-cited paper may not necessarily be a prestigious paper, although in some cases there might be a strong positive correlation between the two measures. PageRank (Brin & Page, 1998) may be used as a measure for both popularity and prestige. PageRank was introduced to prioritize web pages when a keyword search is performed in a search engine. Although originally defined to discover the connectivity of webpages, PageRank could also be extended to find the citation link between papers. Consider paper A that has been cited by other papers; namely, $T_1, \ldots, T_n,$ where paper T_i has citations $C(T_i)$. In this case, the PageRank of paper A (denoted by $PR(A)$) in a network of N papers can be calculated as:

$$PR(A) = \frac{(1-d)}{N} + d\left(\frac{PR(T_1)}{C(T_1)} + \cdots + \frac{PR(T_n)}{C(T_n)}\right),$$

where the parameter d is a damping factor between 0 and 1 that represents the fraction of random walks that continue to propagate along the citations.

The PageRank forms a probability distribution over papers, so the sum of all papers' PageRanks will be equal to one. Using this formula, PageRank is calculated based on an iterative algorithm, and corresponds to the principal eigenvector of the normalized citation matrix of the papers. In the original Google PageRank algorithm of Brin and Page (1998), the parameter d was chosen to be 0.85. This value was prompted by the anecdotal observation that an individual surfing

Table 8
International collaboration statistics.

Country 1	Country 2	No of papers	Country 1	Country 2	No of papers
China	United States	21	Singapore	United States	7
China	Hong Kong	19	Iran	United States	6
Canada	United States	18	Taiwan	United States	6
South Korea	United States	14	Hong Kong	United Kingdom	6
India	United States	10	Canada	China	6
Hong Kong	United States	10	Canada	Iceland	5
Spain	United States	9	France	United States	5
Turkey	United States	9	China	United Kingdom	5
United Kingdom	United States	8	Iceland	United States	4
Germany	United States	7	Netherlands	United States	4

Table 9
The top 10 papers using a citation measure.

Author (year)	Journal	Local citation[a]	Global citation[b]
Tsiakis et al. (2001)	*Industrial and Engineering Chemistry Research*	37	205
Petrovic et al. (1998)	*European Journal of Operational Research*	27	159
Sabri and Beamon (2000)	*Omega*	22	201
Swaminathan et al. (1998)	*Decision Sciences*	21	391
Petrovic et al. (1999)	*International Journal of Production Economics*	20	172
Cachon and Lariviere (2005)	*Management Science*	18	673
Jung et al. (2004)	*Computers and Chemical Engineering*	17	96
Chan and Kumar (2007)	*Omega*	17	342
Chan (2003)	*International Journal of Advanced Manufacturing Technology*	16	155
Wu and Olson (2008)	*International Journal of Production Economics*	15	125
Gupta and Maranas (2000)	*Industrial and Engineering Chemistry Research*	15	93

[a] Local citation: citation within the 1108 papers.
[b] Global citation: the overall Scopus citation.

Table 10
Top 10 papers using a PageRank measure.

Author (year)	PageRank	Local citation[a]	Global citation[b]
Tsiakis et al. (2001)	0.0134	37	205
Swaminathan et al. (1998)	0.0113	21	391
Mirhassani et al. (2000)	0.0104	10	58
Petrovic et al. (1998)	0.0101	27	159
Gupta and Maranas (2000)	0.0088	15	93
Petrovic et al. (1999)	0.0082	20	172
Cachon and Lariviere (2005)	0.0082	18	673
Bernstein and Federgruen (2005)	0.0080	10	220
Bernstein and Federgruen (2004)	0.0079	9	48
Chan (2003)	0.0071	16	155

[a] Local citation: citation within the 1108 papers.
[b] Global citation: the overall Scopus citation.

the web will typically follow about six hyperlinks, corresponding to a leakage probability $1/6 \cong 0.15 = (1 - d)$, before becoming either bored or frustrated with the search and beginning a new search. In the context of citations, entries in the reference list of a typical paper are collected following somewhat shorter paths of average length 2 (Chen, Xie, Maslov & Redner, 2007), making the choice $d = 0.5$ more appropriate for a similar algorithm applied to the citation network.

Table 10 shows the top 10 papers based on a PageRank measure. For this study's 1108-node network, PageRank values vary between zero and 0.0134. It can be seen that a higher number of local and global citations cannot guarantee the 'prestige' of a paper. For example, Sabri and Beamon (2000) is a high-ranked paper (ranked the third in Table 9), but not among the top 10 prestigious papers in Table 10. Equally, there are prestigious papers that are not highly-ranked (e.g. Bernstein & Federgruen, 2004, 2005; Mirhassani et al., 2000; Swaminathan et al., 1998).

4.3. Co-citation analysis

A co-citation network consists of a set of nodes representing journal articles and a set of edges or links representing the co-occurrence of the nodes (articles) in other papers (Leydesdorff, 2011). Therefore, two publications are considered to be co-cited if they appear together in the reference lists of other documents. Papers which are more often cited together are more likely to present similar subject areas or be related (Hjørland, 2013). The co-citation map visualization is a form of exploratory data analysis (EDA) that relies on graph theory to explore the data structure (Pampel, 2004).

The initial co-citation mapping with Gephi revealed that 262 articles out of a total of 1108 have been co-cited by other papers within this sample. When opening the '.NET' file in Gephi for the first time, the positioning of the nodes in the co-citation map is randomly generated by the software. This layout has no discernible pattern, which is not surprising due to the random nature of the positioning. The nodes have identical sizes, but different (x, y) coordinates. Gephi offers a variety of algorithms for creating different layouts. Force Atlas is a force-driven algorithm and the most recommended layout by the developers in terms of simplicity and readability. The network is arranged in a way that linked nodes attract and non-linked nodes repulse each other. It also allows for the manual adjustment of the repulsion strength, gravity, speed, node size and other characteristics (Bastian et al., 2009). With this algorithm, the most connected nodes move to the center of the network while the more isolated (less connected) nodes move to the borders.

Fig. 3a illustrates the Force Atlas layout of the proposed 262-node co-citation map. Co-cited papers (represented by nodes) are connected and the weakly connected nodes are positioned farther from the center. The remote pairs of nodes (weakly connected to the rest of the network) are seen as '*outliers*' and are excluded for data clustering and literature classification purposes in the next sections. Excluding these pairs of remote nodes results a network with 236 nodes and 945 edges. Our co-citation analysis in this section will be based on the resulting 236-node network shown in Fig. 3b.

4.3.1. Literature classification: data clustering

The nodes of a network can be divided into 'clusters' or '*modules*' where the connection (density of edges) is greater between the nodes of the same cluster compared to those of different clusters (Clauset et al., 2004; Leydesdorff, 2011; Radicchi et al., 2004). In a co-citation network, a cluster can be seen as a group of well-connected publications in a research area with limited connection to publications in other clusters or research areas. Data clustering (also termed modularity) has been used in the past as a classification tool for grouping of a set of given publications (Radicchi et al., 2004). It allows for the topological analysis of a co-citation network, identifying topics, interrelations, and collaboration patterns. Data clustering has received increasing attention from scholars and research organizations turning it into a critical research field in social network analysis (Blondel et al., 2008).

The default clustering tool in Gephi is based on the Louvain algorithm, an iterative optimization model that aims to determine the optimal number of partitions that maximize the modularity index (Blondel et al., 2008). The modularity index of a partition is a scalar value between −1 and +1 that measures the density of links inside communities versus the links between communities. According to Blondel et al. (2008), for a weighted network (i.e. networks with weighted links, such as the number of co-occurrence of two articles in the reference list), the modularity index Q can be calculated as:

$$Q = \frac{1}{2m} \sum_{ij} \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta(c_i,\ c_j),$$

where A_{ij} represents the weight of the edge between nodes i and j, k_i is the sum of the weights of the edges attached to node i ($k_i = \sum_j A_{ij}$),

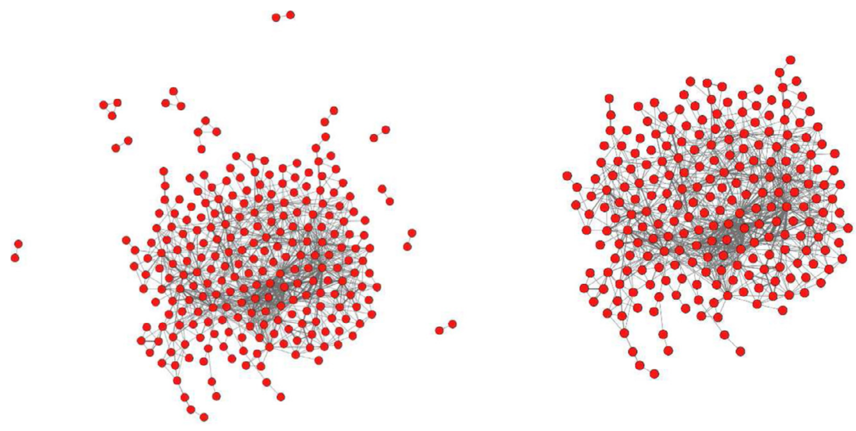

Fig. 3. The Force Atlas layout of the co-citation network. (a) The initial 262-node co-citation network, (b) the 236-node co-citation network after removing the remote nodes.

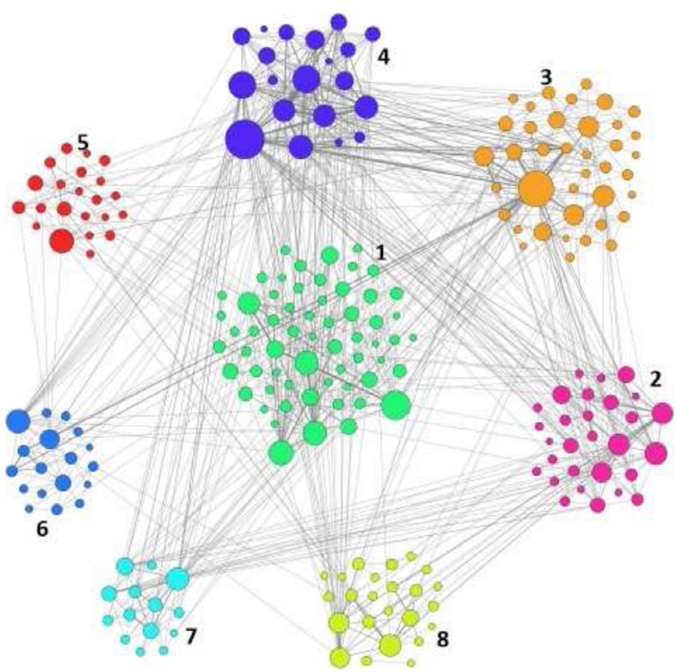

Fig. 4. The positioning of the eight literature clusters.

c_i is the community to which node i is assigned, $\delta(u, v)$ equals 1 if $u = v$; and equals 0, otherwise, and finally $m = \frac{1}{2}\sum_{ij} A_{ij}$.

Applying this algorithm to the filtered 236-node co-citation network in Gephi resulted in the creation of 10 clusters. The number of papers in each cluster varies from only three articles in cluster 10–61 articles in cluster 1, the largest module. Because clusters 9 and 10 contain only three and six papers; respectively, they do not seem to be significant to be considered as major research areas at this point in time. For this reason, we have excluded these two clusters from our analysis and complete our clustering analysis based on the remaining eight clusters of 227 nodes in the remainder of this section. Fig. 4 illustrates the positioning of and interaction among the eight clusters. Obviously, the thickness of an arc between two nodes/papers shows the degree frequency for co-occurrence of the two papers in the reference list of other papers. The modularity index for this network is equal to 0.532 which indicates the very strong relationship between the nodes within each cluster and yet a relatively strong relationship between the nodes of different clusters.

To determine the area of research focus for each cluster, we need to identify the “lead papers” of each cluster. A PageRank measure was used for this purpose (see Table 11 for a list of lead papers). In a co-citation network, the PageRank algorithm takes into account how many times a paper is co-cited with other papers (the ‘popularity’ measure) and how many times it is co-cited with highly co-cited papers (the ‘prestige’ measure). Most of the papers in this study with high PageRank also possess a high citation count. To find out the area of research focus of each cluster, we analyzed and evaluated the contents of all lead papers of each cluster. For example, we observed that all 10 lead papers in cluster 3 have clear focus on modeling supply chain design and/or facility location issues under uncertainty; hence, this cluster was labeled as “uncertainty modeling in supply chain network design and facility location”. To avoid possible conflicting judgments, all four authors of this paper were involved in the cluster labeling process. Table 12 summarizes the result of our classification of research areas associated with those eight clusters depicted in Fig. 4.

4.3.2. Analysis of the primary research clusters

As discussed in Section 4.3.1, our literature mapping and network analysis of the field identifies eight primary research clusters (see Table 12). Additional statistics of these clusters indicate that the average PageRank is significantly higher for cluster 7 (sustainability risk analysis), while its connection with other clusters is considerably weaker than others. In fact, cluster 7 has only limited connections to supply chain uncertainty modeling research areas (clusters 3 and 4) and no connection to other research clusters. This observation can provide an important and interesting insight. Sustainability risks have been identified and discussed in many highly-ranked and prestigious studies, but the area is yet to grow, work closely in conjunction with other research areas, and act as a mediator passing knowledge from one research area to another. We see this as an important and demanding future research direction.

Identifying contributing journals to each research cluster can help determining the most related journal outlets in each area. Table 13 shows the top five contributing journals for each cluster. *International Journal of Production Economics* is the only major contributor to all eight research areas and the lead journal in four out of eight clusters. Another analysis can be also completed to investigate the performance of the contributing journals to all research clusters in terms of both quantity and quality of the published papers, using PageRank as a quality measure (PageRank = popularity + prestige).

Table 11
The lead papers of each cluster using a PageRank measure.

Cluster 1	Cluster 2	Cluster 3	Cluster 4
Chan (2003)	You and Grossmann (2008)	Tsiakis et al. (2001)	Sabri and Beamon (2000)
Kumar et al. (2006)	Pan and Nagi (2010)	Azaron et al. (2008)	Petrovic et al. (1998)
Chan and Kumar (2007)	Bernstein and Federgruen (2004)	Blackhurst et al. (2004)	Jung et al. (2004)
Kumar et al. (2004)	Longinidis and Georgiadis (2011)	Mirhassani et al. (2000)	Chen and Lee (2004)
Wu and Olson (2008)	Pishvaee and Torabi (2010)	Miranda and Garrido (2004)	Lee and Kim (2002)
Chan et al. (2008)	Sawik (2011)	Gumus et al. (2009)	Petrovic et al. (1999)
Jain et al. (2008)	Poojari et al. (2008)	Chan and Chung (2004)	Petrovic (2001)
Xu and Nozick (2009)	Fandel and Stammen (2004)	Shang et al. (2004)	Liang (2007)
Kumar et al. (2008)	Schmitt et al. (2010)	Aghezzaf (2005)	Lim et al. (2006)
Kull and Talluri (2008)	Mohammadi Bidhandi and Mohd Yusuff (2011)	Chan et al. (2005)	Leung et al. (2006)
Cluster 5	**Cluster 6**	**Cluster 7**	**Cluster 8**
Swaminathan et al. (1998)	Braun et al. (2003b)	Kim et al. (2011a)	Cachon and Lariviere (2005)
Tsay (1999)	Disney and Towill (2002)	Sodhi and Tang (2009)	Kouvelis and Milner (2002)
Zhao et al. (2001)	Villegas and Smith (2006)	Dal-Mas et al. (2011)	Agrawal et al. (2002)
Feng et al. (2010)	Schwartz and Rivera (2010)	Kim et al. (2011b)	Bernstein and Federgruen (2005)
Munson and Rosenblatt (2001)	Braun et al. (2003a)	Giarola et al. (2012)	Hsieh and Wu (2009)
Erhun et al. (2008)	Moyaux et al. (2007)	Awudu and Zhang (2012)	Van Mieghem (1999)
Ferguson (2003)	Wangphanich et al. (2010)	Rentizelas et al. (2009)	Hsieh and Wu (2008)
Lee, Padmanabhan and Whang (2004)	Schwartz et al. (2006)	Awudu and Zhang (2013)	Yao et al. (2008)
Chan and Chan (2006)	Wang and Rivera (2008)	Gebreslassie et al. (2012)	Seifert et al. (2004)
Longo and Mirabelli (2008)	Riddalls and Bennett (2002)	Carneiro et al. (2010)	Song et al. (2008)

Table 12
Literature classification: the primary research clusters.

Cluster	No. of papers	Research area
1	61	Upstream supply chain risks (supply uncertainty and supplier evaluation issues)
2	29	Downstream supply chain risks (demand uncertainty issues)
3	39	Uncertainty modeling in supply chain network design and facility location
4	20	Uncertainty modeling in tactical/operational supply chain planning
5	22	Supply and demand forecasting analysis
6	18	Uncertainty modeling in inventory management and process control
7	14	Sustainability risks (focus on energy/biomass/biofuel/ethanol supply chains)
8	24	Uncertainty in purchasing and retail sourcing (case studies)

Table 13
Top five contributing journals in each research area.

1. Upstream SC risks	2. Downstream SC risks
International Journal of Production Economics	*International Journal of Production Economics*
European Journal of Operational Research	*Computers and Chemical Engineering*
Computers and Industrial Engineering	*European Journal of Operational Research*
International Journal of Production Research	*Expert Systems with Applications*
Omega	*Computers and Operations Research*
3. Uncertainty in SC network design	**4. Uncertainty in tactical/operational SC planning**
European Journal of Operational Research	*International Journal of Production Economics*
International Journal of Production Economics	*European Journal of Operational Research*
International Journal of Production Research	*Journal of the Operational Research Society*
International Journal of Advanced Manufacturing Technology	*Computers and Industrial Engineering*
Industrial and Engineering Chemistry Research	*Production Planning and Control*
5. Supply and demand forecasting analysis	**6. Uncertainty in inventory management/control**
International Journal of Production Research	*International Journal of Production Research*
IIE Transactions (Institute of Industrial Engineers)	*Computers and Industrial Engineering*
IEEE Transactions on Industrial Informatics	*International Journal of Integrated Supply Management*
Management Science	*Annual Reviews in Control*
International Journal of Production Economics	*International Journal of Production Economics*
7. Sustainability risks	**8. Uncertainty in purchasing and retail sourcing**
Biomass and Bioenergy	*European Journal of Operational Research*
AIChE Journal	*International Journal of Production Economics*
Bioresource Technology	*Management Science*
Renewable and Sustainable Energy Reviews	*Naval Research Logistics*
International Journal of Production Economics	*Manufacturing and Service Operations Management*

Fig. 5 illustrates this quantity versus quality analysis. We find that in most cases there is a positive correlation between the quantity and quality of published papers. The three primary contributors to the field are *International Journal of Production Economics*, *European Journal of Operational Research* and *International Journal of Production Research*, occupying the upper right portion of the diagram. *Management Science* holds the greatest 'quality/quantity ratio' among all journals.

We also complete a dynamic co-citation analysis to help understand the evolution of clusters over time. The evolution of the field

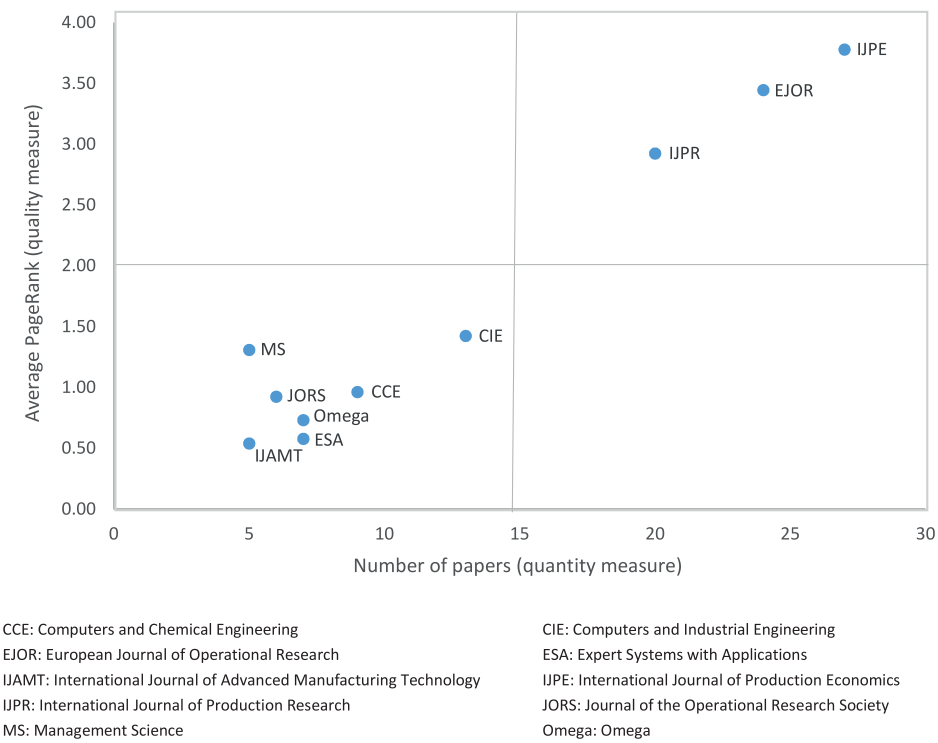

Fig. 5. Major contributing journals to the development of SCRM research clusters: a quantity versus quality analysis.

since 1978 is graphically shown in Fig. 6. The size of a node for each layout represents the PageRank of the article; hence, the larger the size of a node, the more highly-cited and prestigious the corresponding paper. While all clusters have shown a relatively smooth and constant evolution over time, a clear insight from Fig. 6 is that SCRM at the design and tactical/operational planning levels (clusters 3 and 4 respectively) as well as demand/supply forecasting (cluster 5) appeared early and evolved quickly over the first two decades. Sourcing/supply uncertainty modeling and the related case studies (clusters 1 and 8 respectively) emerged next and have also evolved quite rapidly. Sustainability risk analysis is the youngest among all the areas, with significant potential to grow and contribute to other areas in the years to come.

The sustainability risk analysis of supply chains, chronologically, is one of the later topical areas. Also, this sub-field seems to be most supported from literature in the environmental engineering and energy areas, as noted in Table 13 with the top journals publishing this topic. The potential arises when considering that the topic has yet to reach the operations and management journals. In addition, given that the focus has been on energy and environmental issues with respect to sustainability risk management in supply chains, growth in social sustainability risk has significant potential (Brandenburg, Govindan, Sarkis & Seuring, 2014; Fahimnia, Sarkis & Davarzani, 2014). Overall, the field of sustainable supply chain management has seen recent and substantial growth. It can be expected that sustainability and supply chain risk management will eventually be one of the more investigated areas as the sustainable supply chain field expanding more into managerial and methodological operations journals and addressing social dimensions of sustainability.

4.3.3. *Classification of generative research areas*

A second clustering and co-citation analysis is now completed to identify and analyze the papers that are foundational and generative of the eight research areas identified in Section 4.3.1 (see Table 12). For this analysis, all papers appearing in the reference lists of the initial 1108 modeling papers are extracted. This exercise finds 25,799 papers, 84 percent of which (21,572 papers) are only cited in one paper and hence cannot be included in a co-citation analysis (note that for two papers to be considered co-cited, they need to appear together in reference list of other papers). To target the more influential studies within this network, we complete a co-citation analysis for papers that are cited at least five times. This creates a 708-node network with 22,476 edges, a high-density network with a modularity index of 0.471.

The modularity tool of Gephi creates seven clusters for this network. We call these "*generative clusters*" or "*generative research areas*" because they have provided the field with various foundational knowledge, concepts, theories, tools, and techniques. The positioning of the generative clusters is illustrated in Fig. 7. We use a similar labeling approach introduced in Section 4.3.1 to characterize the seven generative clusters (i.e. analyzing and evaluating the contents of the lead papers of each cluster by all four authors of this paper). Table 14 shows the seven generative research areas that have been feeding the SCRM modeling efforts. The table summarizes the careful evaluation of the top-10 papers from each cluster.

We now investigate the relationship between the risk modeling research areas and the generative research areas. The citations within the risk modeling papers in different clusters are examined to explore the generative research areas to which they are most closely related. For example, 53 percent of the publications in cluster 4 of the risk modeling clusters ("uncertainty in tactical/operational SC planning") are closely related to the 'fuzzy modeling' research area ("supply chain planning in a fuzzy environment"). A similar analysis for overlaps in generative and topical publications in all clusters results in findings shown in Table 15. The table summarizes which of the seven generative clusters have been contributing to the risk modeling research clusters.

This information of generative areas and risk modeling areas is important since it also provides opportunities to identify gaps in the research streams. Some generative areas may be more mature in specific risk modeling areas. For example upstream and downstream supply chain risk topics have had a number of generative areas

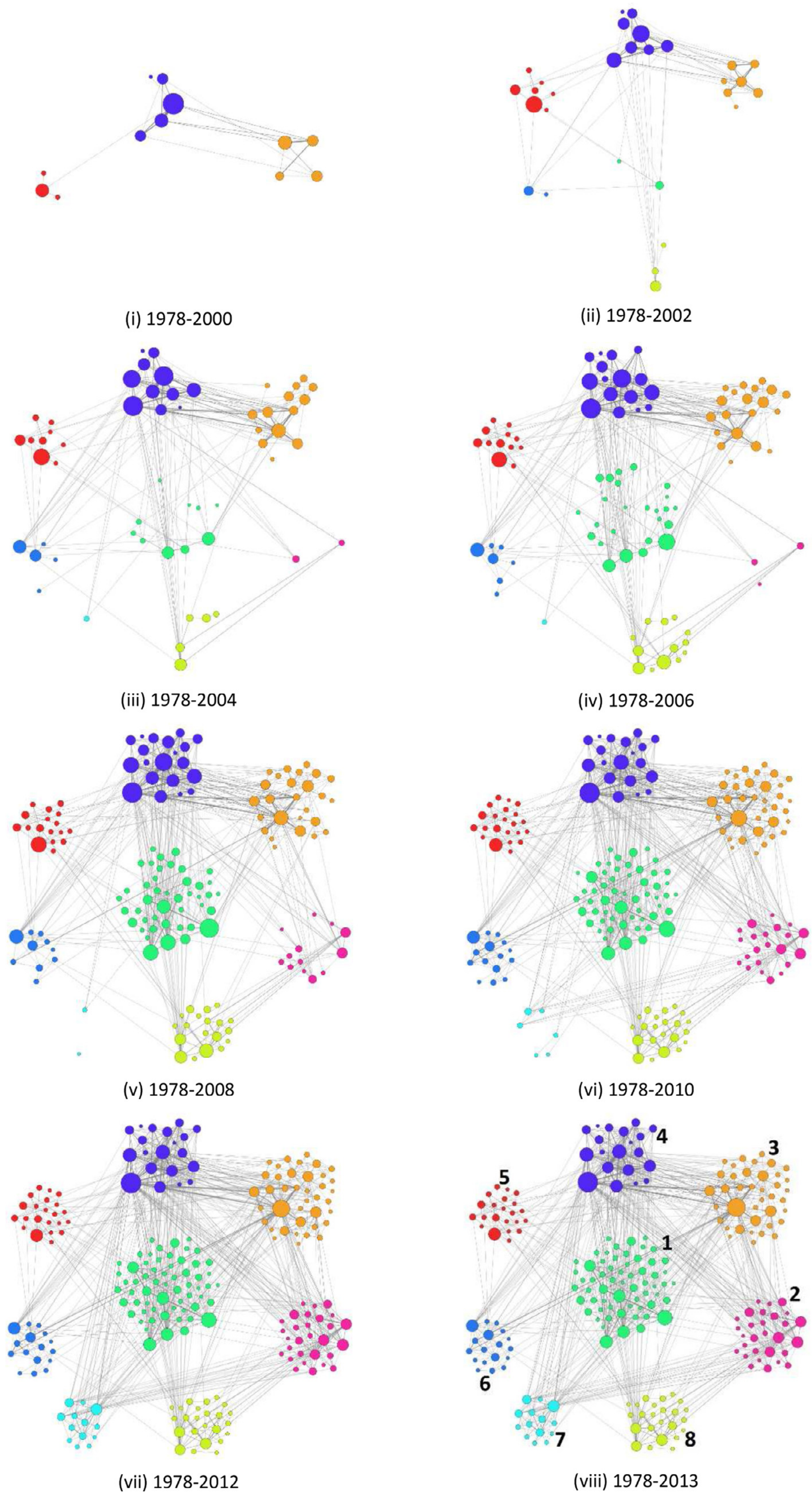

Fig. 6. The evolution of SCRM research over time, (i) 1978–2000, (ii) 1978–2002, (iii) 1978–2004, (iv) 1978–2006, (v) 1978–2008, (vi) 1978–2010, (vii) 1978–2012, (viii) 1978–2013.

Table 14
The seven generative research areas.

Generative cluster	No. of papers	Research area
1	82	Fuzzy modeling for strategic/tactical/operational decision-making
2	118	Information sharing: supply chain coordination, bullwhip effect, dynamic modeling
3	120	Risk theories and conceptual risk mitigation strategies
4	98	Pricing and contracting: mathematical models and solution techniques
5	28	Performance measurement: conceptual models and performance metrics for design and management of agile and lean supply chains
6	115	Supplier/vendor selection: methods and criteria
7	147	Supply chain network design and facility location: mathematical models and solution techniques

Table 15
Relationship between the generative research areas and primary risk modeling research areas.

Generative research area	The most related risk modeling research areas
1. Fuzzy modeling	2. Downstream supply chain risks
	4. Uncertainty in tactical/operational supply chain planning
2. Information sharing	1. Upstream supply chain risks
	3. Uncertainty in supply chain network design
	8. Uncertainty in purchasing and retail sourcing
3. Risk theories	1. Upstream supply chain risks
	2. Downstream supply chain risks
	3. Uncertainty in supply chain network design
	6. Uncertainty in inventory management and process control
4. Pricing and contracting	3. Uncertainty in supply chain network design
	5. Supply and demand forecasting analysis
	8. Uncertainty in purchasing and retail sourcing
5. Performance measurement	1. Upstream supply chain risks
6. Supplier/vendor selection	1. Upstream supply chain risks
7. Network design and facility location	2. Downstream supply chain risks
	3. Uncertainty in supply chain network design
	6. Uncertainty in inventory management and process control
	7. Sustainability risks

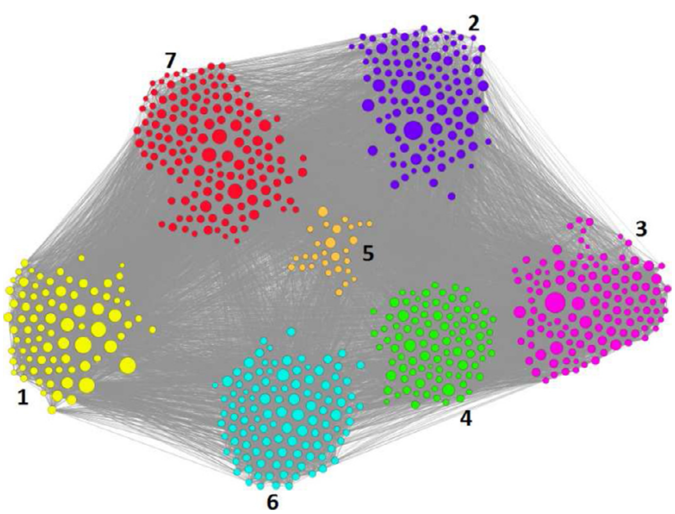

Fig. 7. The positioning of the generative clusters.

Table 16
The top five papers based on article type.

Literature review	Concept and theory
Tang (2006)	Lee et al. (1997)
Beamon (1998)	Silver et al. (1998)
Thomas and Griffin (1996)	Davis (1993)
Cohen and Lee (1988)	Lee and Billington (1993)
Min and Zhou (2002)	Kleindorfer and Saad (2005)
Mathematical modeling	**Solution method**
Tsiakis et al. (2001)	Zadeh (1965)
Gupta and Maranas (2003)	Saaty (1980)
Santoso et al. (2005)	Forrester (1961)
Petrovic et al. (1998)	Birge and Louveaux (1997)
Ghodsypour and O'Brien (1998)	Bellman and Zadeh (1970)

involved in their evaluation. But, sustainability risk evaluation has had only one generative topic. This observation further supports the potential for growth, as other generative approaches and concepts can be applied to help this area further mature. Research growth in other SCRM modeling areas can also occur through a similar identification of various permutations between the generative fields and SCRM analytical modeling literature.

In another observation, we found that papers in generative research areas can be classified into four categories based upon their article type: (1) literature reviews, (1) concepts/theories, (3) mathematical models, and (4) solution methods. Table 16 shows the top five papers of each category using the PageRank measure. Papers in 'concepts/theories' category help with setting the foundational theory building and sending-making of the field. The mathematical modeling papers are mostly the base models for particular problem types and thus many of the citing papers are the extensions of these models. The solution method papers provide the innovative tools, methods and techniques to deal with quantitative SCRM problems (e.g. fuzzy modeling, stochastic modeling, system dynamics, discrete event simulation, etc.).

5. Conclusions and directions for future research

Supply chain risk management (SCRM) has established as an important research area. The increasing number of publications in this area confirms this trend. We have used bibliometric and network analysis tools to analyze quantitative SCRM literature, examine the evolution of this research area, and identify emerging trends. Adopting different objective measures, our study generated the following results that can help new researchers to establish their research agenda in this field. First, we have identified the contributions provided by researchers and universities in different geographical regions. This information is useful for scholars and students who are interested in conducting SCRM research with researchers at various universities. Second, we have identified research trends in different streams of research. These trends can help identify the streams that may have matured or become more saturated and those that are gaining momentum.

The following major conclusions can be drawn from this study on quantitative SCRM research articles: (1) A frequency analysis showed that quantitative, analytical and formal modeling of SCRM research output is growing rapidly especially since 2001; (2) Most formal modeling SCRM research is conducted by researchers at universities located in the United States and Asia (China, Hong Kong, India, Iran, Singapore, Taiwan); (3) Most quantitative SCRM research articles are published in three major journals, including *International Journal of Production Economics*, *European Journal of Operational Research*, and *International Journal of Production Research*; (4) Formal modeling SCRM research can be classified into eight different categories/streams from which we recognize "supply uncertainty" as a matured area, perhaps getting saturated, and "sustainability risk" as an emerging area; and (5) Generative research topics and areas show what additional possibilities exist for cross-fertilization of concepts, tools and theories for both mature and emergent areas of formal SCRM modeling research.

These findings and conclusions have some important implications. It appears European journals are facilitating the dissemination of the knowledge developed by researchers located in the United States and Asia. Sustainability risk is an emerging stream in the SCRM arena with great potential for researchers to make major contributions. The emergence is quick with substantial cross-fertilization available among concepts and tools from other areas. This finding is consistent with a remark made by Tang and Zhou (2012) noting that the research agenda is maturing in the area of recycling and remanufacturing, while environmental and social sustainability risks are two nascent areas that deserve future attention. Overall, combining the relatively subjective perspectives of previous reviews of SCRM and supply chain management and the relatively objective and rigorous network and bibliometric analysis presented in this paper can help researchers establish their research agendas in SCRM quantitative, formal modeling research. It is expected that this field will continue to grow as practitioners face challenges that research can help solve.

Using the actual citations observed in the quantitative SCRM literature, our network and bibliometric analysis enabled us to identify influential articles and researchers in an objective manner. However, this approach has limitations that deserve further investigations. First, the keyword structure was designed through a number of trials to ensure the most effective and feasible search space. However, there may be some related works that this keyword structure did not capture because we used general modeling keywords and not specific techniques and tools in the keyword search. By including more specific and additional keywords, we could generate a larger pool of papers. However, analyzing the network associated with a larger pool of papers is beyond the capability of the available network analysis software. Therefore, there is an opportunity for further research as the network analysis software is further developed.

Second, the categorizations and titles of both the actual modeling categories and generative studies are not necessarily homogenous. Multiple and different topical areas exist in some areas and a more nuanced, sub categorization evaluation may provide ample room for identification of sub-clusters or additional interpretations and insights. Third, the Scopus database is relatively comprehensive and has certain advantages as a database, but is not as encompassing in capturing information as Google Scholar. Not all journals that are on the listing appeared in Scopus for all years. Thus, some early publications may have been missed. Also, Scopus may have limited electronic information before the 1978 time period, potentially limiting pre-1978 papers that may have been captured in older electronic systems. Finally, the literature mapping and network analysis methodology presented in this paper shows how a subject area can be objectively reviewed to identify the key papers and investigators. However, the methodology is not able to "interpret" the knowledge in these papers to explore the underlying reasons why certain papers have been central to the development of the field (syntax versus semantics). Future review efforts can focus on the development of tools and methodologies to address this limitation.

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