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Tactical supply chain planning models with inherent flexibility: definition and review

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Abstract Supply chains (SCs) can be managed at many levels. The use of tactical SC planning models with multiple flexibility options can help manage the usual operations efficiently and effectively, whilst improve the SC resiliency in response to inherent environmental uncertainties. This paper defines tactical SC flexibility and identifies tactical flexibility measures and options for development of flexible SC planning models. A classification of the existing literature of SC planning is introduced that highlights the characteristics of published flexibility inclusive models. Additional classifications from the reviewed literature are presented based on the integration of flexibility options used, solution methods utilized, and real world applications presented. These classifications are helpful for identifying research gaps in the current literature and provide insights for future modeling and research efforts in the field.

Keywords Supply chain · Tactical planning · Flexibility · Integration · Uncertainty · Review

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1 Introduction

Uncertainty is an inherent characteristic of today's business environment. Some typical sources of uncertainty may include demand and supply interruptions, lead time variability, exchange rate volatility, and capacity availability (Gong 2008; Das 2011; Merschmann and Thonemann 2011). Flexibility has been recognized in various disciplines as a strategy to manage different types of uncertainty. The definition of flexibility varies from one discipline/context to another with confusion surrounding its dimensions and stages (Sawhney 2006). In manufacturing, flexibility is referred to various states a system can adopt to manufacture different product types at different volumes (Upton 1995; Slack 1983). That is the ability of a manufacturing system to react by shifting between various states of the system with little penalty in time, cost and performance (Swafford et al. 2006; Upton 1995). Manufacturing flexibility and its measures have been well studied in previous research (Beamon 1999; Yi et al. 2011; Swafford et al. 2006; Koste and Malhotra 1999; Koste et al. 2004; Borenstein 1998).

Supply chain (SC) is an integrated network of organizations involved in the physical flow of products from suppliers to customers (Fahimnia et al. 2013b). A flexible SC is able to respond more quickly to various interruptions in supply and demand as well as changes in other environmental parameters such as lead-time, exchange rate, and capacity limits (Stevenson and Spring 2007; Merschmann and Thonemann 2011). Supply chain flexibility (SCF) has a broad process-based view that incorporates the flexibility of core processes including procurement/sourcing, manufacturing, transportation, and warehousing (Merschmann and Thonemann 2011; Vickery et al. 1999). Research in the context of SCF has evolved over the past decade from infancy to theoretical and conceptual development to modeling efforts and empirical exploratory studies (Stevenson and Spring 2007; Beamon 1999; Sawhney 2006).

Vast literature investigating SCF at the strategic level (known as SC robustness) exists. At the strategic level the objective is to redesign or reconfigure the network or its elements enabling it to adapt quickly and efficiently to major disruptions (Klibi et al. 2010; Swafford et al. 2006). For example, several quantitative models have been developed for the optimal design of SCs when disruptions occur in the downstream SC, that is at the demand side (Pan and Nagi 2010; Georgiadis et al. 2011; Shen 2006; Guillén et al. 2006; You and Grossmann 2008; Gupta et al. 2000). Some others have studied robust SC network design when disruptions are likely to occur at the supply side or upstream SC (Lin and Wang 2011; Peidro et al. 2009b).

Strategic robustness and flexibility through redesigning or reconfiguring an existing network can be expensive. Corporations with established SC configurations are reluctant to adopt costly strategies for mitigating major, yet less frequent, SC disruptions such as natural disasters and financial/political chaos (Sodhi and Tang 2012). Instead, the more frequent uncertainty types such as interruptions in supply, demand, production, and logistics need to be tackled more carefully.

From a practical perspective, one approach to adjust the flexibility of an existing SC is to develop and analyze a SC planning model with inherent flexibility options incorporated into it. The use of such tools can help a corporation manage its usual operations efficiently and effectively, whilst improving its SC resiliency when facing supply, demand, production, and logistics interruptions and variances. A primary issue is that SCF is achieved only if all key processes across the SC (i.e. procurement, manufacturing and distribution processes) have the ability to rapidly respond to environmental changes (Sánchez and Pérez 2005; Vickery et al. 1999; Swafford et al. 2006; Merschmann and Thonemann 2011;

Hodder and Triantis 1993). Complexity arises in the development of tactical SC planning models that incorporate multiple flexibility options for all key SC processes.

Despite the dynamic and rapid evolution of research in this field, there has been no attempt to present a review of the existing literature of tactical SC planning with a comprehensive flexibility classification of published models (i.e. the multiplicity of flexibility options). In this paper, we attend to this important issue. A framework is developed in Sect. 2 for defining and quantifying SCF at the tactical planning level by identifying tactical SCF measures and options. Section 3 classifies the published tactical SC planning/optimization models based on the flexibility options incorporated. Other classifications are also presented according to the integration of flexibility measures used, solution methods utilized, and real world applications. These classifications provide important insights and suggest potential directions for future research in the field, presented in Sect. 4.

2 Defining SCF and its measures

'Flexibility' and 'Robustness' are the two terms that have been used frequently, and in some cases interchangeably, when dealing with SC uncertainties. We differentiate between the two. Robustness decisions are taken at the strategic level and a robust system is meant to remain unaffected or less affected by major less-frequent SC disruptions (e.g. labor strikes, flood and earthquake disasters). On the other hand, a flexible SC is meant to be quickly adaptable in the presence of more-frequent uncertainties such as interruptions in supply, demand, manufacturing, and logistics operations. Flexibility is often present in the form of volume flexibility, delivery flexibility and operational flexibility (Schütz and Tomasgard 2011; Kumar 1988). SC robustness is out of area of our investigation and instead we place our focus on measuring SCF at the tactical (mid-term) planning level.

Unless flexibility measures are adequately defined, it is not possible to compare the flexibility of one SC against another (Gunasekaran 1999; Lummus et al. 2003; Vickery et al. 1999; Stevenson and Spring 2007). SCF measures have been studied in some of the past research (Pujawan 2004; Giachetti et al. 2003; Vickery et al. 1999; Beamon 1999; Stevenson and Spring 2007). A number of potential flexibility categorizations have been given, some of which include the followings:

- Volume flexibility: the ability to expand the production capacity, e.g. capacity expansion, overtime production and additional production shifts (Sabri and Beamon 2000);
- Delivery flexibility: the ability to change delivered amount and delivery date, such as a backlogging option (Sabri and Beamon 2000);
- Operational decision flexibility: the ability to respond to changes in operational decisions such as changes in the bill of material and assignment of jobs to machines (Sánchez and Pérez 2005);
- Storage flexibility: the ability to respond to sudden changes in supply, demand and production, such as the use of just-in-case inventory (Schütz and Tomasgard 2011);
- Process flexibility: the ability to manufacture a range of product types at each manufacturing plant (Garavelli 2003; Sánchez and Pérez 2005);
- Logistics flexibility: the ability to adopt different logistics strategies to deliver the final products to end-users (Garavelli 2003; Sánchez and Pérez 2005);
- Vendor flexibility: flexibility options offered by different vendors that support manufacturing, warehousing or transport operations (Gosling et al. 2010; Swafford et al. 2006); and

- Sourcing flexibility: the ability to reconfigure a SC network through selection or deselection of vendors (Gosling et al. 2010).

SCF can also include flexibility in SC relationships, flexibility in SC design, as well as flexibility in inter-organizational information systems (Stevenson and Spring 2007). A generic framework for formulating SCF measures in procurement, manufacturing and distribution has been proposed (Swafford et al. 2006) that provides a range of operational, tactical and strategic measures for procurement, manufacturing, and distribution processes.

Making use of these existing frameworks (Sodhi and Tang 2012; Stevenson and Spring 2007; Swafford et al. 2006), we present a framework to specifically formulate quantifiable tactical[1] SCF measures. The framework will then be used for classification of published tactical SC planning models. Three key principles that set the foundation for the development of this framework include:

1. For large corporations with established SC configurations, SCF initiatives are less likely to be introduced at the strategic level (i.e. SC design/reconfiguration level) due to substantial investment requirements. Instead, the focus is on effective use of available resources and adjustment of flexibility options to enhance SC responsiveness. We use the term "inherent flexibility" for those flexibility options incorporated in tactical SC planning models.
2. The overall flexibility of a SC depends on the flexibility of all SC processes and their interrelations; hence, the flexibility-related decisions within a SC must be made while considering the available/achievable flexibility options in other SC processes (Gong 2008; Swafford et al. 2006; Stevenson and Spring 2007). In other words, SCF is multi-dimensional and being flexible in one dimension does not necessarily contribute to the overall SC flexibility.
3. It is widely recognized that flexibility options may be employed both reactively and proactively and hence the options may be differently weighted in various environments (Stevenson and Spring 2007; Sawhney 2006). Given the case-specific nature of SCF options, tactical SC planning models can be utilized to determine the weight of each flexibility option and adjust the SC flexibility in certain environments. This weighting scheme helps determine the degree of flexibility required for various SC processes in order to attain the appropriate level of global flexibility.

Figure 1 illustrates a three-dimensional framework quantifying SCF measures that can be used for tactical SC planning and optimization. The three dimensions of SCF include *supply flexibility* (i.e. flexibility in procurement and sourcing processes), *manufacturing flexibility* (i.e. flexibility in manufacturing and assembly processes), and *distribution/logistics flexibility* (i.e. flexibility in transportation and warehousing processes).

A typical manufacturing firm spends between 55 and 80 % of its earned revenue on procurement processes and hence *supply flexibility* options can play a key role in the SC's financial performance (Benton 2010; Burke et al. 2007). At the tactical planning level, supply flexibility can be addressed in two ways: 'make-and/or-buy decisions' and 'sourcing decisions'. A SC can be more flexible in facing common supply disruptions, if certain products are both manufactured in-house and outsourced (Sodhi and Tang 2012).

[1] It is not always easy to discern Tactical from Strategic. Strategic will be defined as a concept that focuses on relatively long term management (over multiple years), with explicit and necessary inclusion of multiple functions within an organization (setting strategies). Tactical is an intermediate time length (monthly, quarterly, up to a year) and one department or function can effectively manage the situation (strategy deployment).

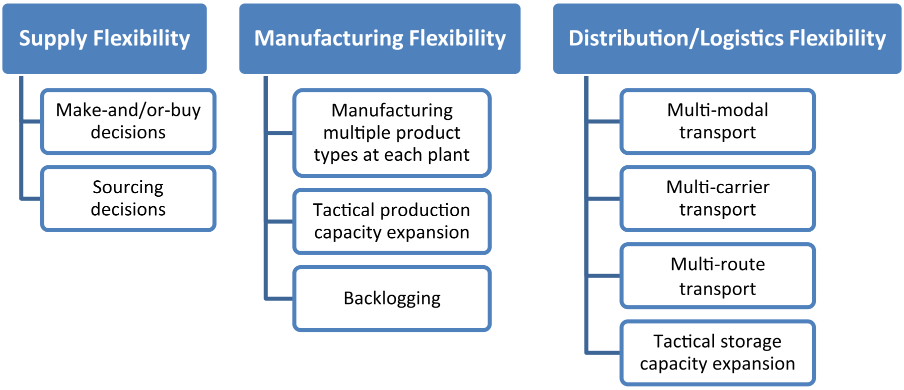

Fig. 1 SCF measures (options) for three flexibility dimensions of tactical SC planning

Make-and/or-buy tactics can be used to build this important flexibility option into tactical SC planning models. Sourcing decisions may include single versus multiple and cross sourcing. While sourcing from a single supplier may incur lower cost per unit through quantity discount and reduced supply management and admin costs, multiple and cross sourcing are the more flexible options enabling a SC to become responsive when facing supply interruptions and demand fluctuations (Burke et al. 2007).

Manufacturing flexibility options at the tactical planning level may include process flexibility (i.e. manufacturing of multiple product types at each plant), manufacturing capacity flexibility (i.e. overtime production, additional operating shifts, and other possible mid-term capacity expansion investments), and delivery flexibility (i.e. backlogging to change the delivery date at a certain penalty cost). While process flexibility initiatives are generally practiced at the strategic level (Beamon 1999; Schütz and Tomasgard 2011), it has been argued that manufacturing firms can effectively mitigate demand risks by establishing some additional tactical process flexibility at each plant (Jordan and Graves 1995). This can be through the addition of multipurpose machines and multi-skill labors enabling a manufacturing plant produce multiple product types in one manufacturing plant.

Distribution/logistics flexibility at the tactical planning level can be addressed through transportation and storage flexibility options. Flexibility options in transport may include the use of multiple modes of transportation (i.e. rail, ocean, road and air), multiple carriers or logistics providers (e.g. TOLL, DHL, FedEx among others), and multiple transport routes to avoid long delays due to local bottlenecks, such as traffic jams. Another approach to enhance the flexibility of a distribution network at the tactical level is to store extra inventory (at rental warehouses) that can be utilized against economies of scale in transport, quantity discount in purchasing, or a manufacturing boom in a certain period.

3 Literature classifications

The methodology we use for the classification of the literature is based on the review strategy suggested by Seuring and Müller (2008). Once the appropriate search terms are identified, the related articles are collected from the Scopus database and stored using the

Endnote bibliography software. To avoid possible conflicting judgments, we involve three researchers (including one junior and two senior scholars) in analysis and classification of the collected literature. Keywords included different combinations of “SC”, “Procurement”, “Production”, “Manufacturing”, “Distribution”, “Logistics” “Model”, “Planning” and “Optimization”. We do not include “Flexibility” as one of the search keywords because our objective is to classify the published ‘tactical SC planning models’ with respect to the inherent flexibility options incorporated. We found that the inclusion of “flexibility” as one of the keywords together with the other aforementioned keywords would considerably reduce the search space resulting in only few related articles. Using the Scopus database[2] and a “title, abstract, keywords” search, manuscripts were located and stored using the Endnote bibliography software. The initial search attempts resulted in 114 related journal articles in tactical SC planning (published optimization models with minimization and maximization objective functions) from which 67 models were identified to incorporate at-least one of the SCF measures/options.

Table 1 shows the contribution of different journals in publishing the tactical SC planning models reviewed in this paper. More than a third of the identified articles were published in four journals. The leading journal, the *International Journal of Production Research* (IJPR), published ten model-based articles that included SCF factors, with the *European Journal of Operational Research* standing in second place with six. These two journals are very much modeling and methodology oriented journals with strong operations and SC management research covered over the years. They also have some of the largest number of issues published per year, with IJPR growing to 24 issues per year. Most of the journals in the top ten in our list are known for operations and SC modeling. The only one that is less-known in these fields is *Industrial and Engineering Chemistry Research*. This was one of the surprising journals in the list since it is sponsored by the American Chemical Society, and focuses on Chemical Engineering and production.

Surprisingly, in Table 1, some of the leading SC, logistics, and decision sciences journals are not included. For example, the *Journal of Supply Chain Management*, the *Journal of Business Logistics*, *Management Science* and *Decision Sciences*, which regularly publish SC modeling research, do not even have one article that addresses SCF dimensions at the tactical level. Although recently the *Journal of Supply Chain Management* has eschewed formal modeling papers, they have historically published a number of modeling articles.

3.1 Classification based on the SCF measures

One classification of the published models can be made based on the SCF measures incorporated. Table 2 groups the published models against the SCF measures they incorporate. Articles were reviewed by each of the three researchers to determine whether articles explicitly covered one of the dimensions listed, at least two people had to agree that

[2] The Scopus database is managed by Elsevier publishing. It is more comprehensive than the Web-of-Science database which would include only ISI indexed journals. Since we are focusing on peer-reviewed journals, it was felt 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 SC peer reviewed articles (Chicksand et al. 2012). Although, by no means exhaustive, we can be pretty confident that the SCOPUS database provides a comprehensive and reliable source for academic literature reviews. 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. One of the limitations of Scopus is limited access to pre-1996 peer reviewed journal articles.

Table 1 Contribution of journals in publishing tactical SC planning models

Journal title	No of articles	% Contribution
International Journal of Production Research	10	14.9
European Journal of Operational Research	6	9
Computer and Industrial Engineering	5	7.5
Industrial and Engineering Chemistry Research	5	7.5
International Journal of Production Economies	4	6
IIE Transactions	4	6
Computers and Operations Research	4	6
Omega	3	4.5
Information Science	2	3
Expert Systems with Application	2	3
Applied Soft Computing	2	3
Production Planning and Control	2	3
International Journal of Advanced Manufacturing Technology	2	3
Computer and Chemical Engineering	2	3
Operations Research	1	1.5
Production and Operations Management	1	1.5
International Journal of Operations and Production Management	1	1.5
Transportation Research Part E: Logistics and Transportation Review	1	1.5
Fuzzy Sets and Systems	1	1.5
Applied Mathematical Modeling	1	1.5
Advances in Engineering Software	1	1.5
Journal of Mathematical Modeling and Algorithms	1	1.5
Mathematical and Computer Modeling	1	1.5
Journal of Manufacturing Technology Management	1	1.5
AICHE Journal	1	1.5
Journal of Global Optimization	1	1.5
Chemical Engineering Science	1	1.5
Applied Mathematics and Computation	1	1.5
Total	67	100

it fit within a category. As can be seen, in many cases published models included more than one dimension. Not surprisingly, manufacturing flexibility received the most attention among the three SCF dimensions. For example, almost all the published models have taken into account *process flexibility* in flexible manufacturing systems; that is manufacturing of multiple product types at each plant. Distribution/logistics flexibility received the least attention among the three SCF dimensions. Multi-route transport has received some attention, while fewer studies in recent years have tried developing multi-modal and multi-carrier transport models. There are only two models studying tactical storage capacity expansion.

There is a positive trend in the use of supply flexibility options at the tactical planning level. In particular, due to the increasing interest in procurement function in the past few years (Burke et al. 2007), studying the cons and pros of multiple sourcing against single sourcing has been an attractive area of research. By the same reasoning, make-and/or-buy

Table 2 Classification of the published models based on the SCF options incorporated

Supply flexibility				
Make-and/or-buy	Chen and Wang (1997) Liang (2008) Peidro et al. (2011) Fahimnia et al. (2012)	Jolayemi and Olorunniwo (2004) Ouhimmou et al. (2008) Mirzapour Al-e-hashem et al. (2011) Varthanan et al. (2012b)	Oh and Karimi (2006) Liang and Cheng (2009) Alemany et al. (2010) Varthanan et al. (2012a)	Chern and Hsieh (2007) Liang (2011) Peidro et al. (2011)
Multiple sourcing	Chen and Wang (1997) Alonso-Ayuso et al. (2003) Yılmaz and Çatay (2006) Lejeune and Ruszczyński (2007) Gunnarsson and Rönnqvist (2008) Che and Chiang (2010) Pal et al. (2011) Nikolopoulou and Ierapetritou (2012)	Dogan and Goetschalckx (1999) Gen and Syarif (2005) Oh and Karimi (2006) Chern and Hsieh (2007) Ouhimmou et al. (2008) Alemany et al. (2010) Peidro et al. (2011)	Jayaraman and Pirkul (2001) Lim et al. (2006) Gunnarsson et al. (2007) Tsai (2007) Peidro et al. (2009a) Peidro et al. (2010) Bashiri et al. (2012)	Jang et al. (2002) Lejeune (2006) Meijboom and Obel (2007) Genin et al. (2008) Torabi and Hassini (2009) Mirzapour Al-e-hashem et al. (2011) Che (2012)
Manufacturing flexibility				
Manufacturing multiple product types at each plant	McDonald and Karimi (1997) Gupta and Maranas (2000) Gupta and Maranas (2003) Souza et al. (2004) Park (2005) Lejeune (2006) Chern and Hsieh (2007) Meijboom and Obel (2007) Liang (2008) Genin et al. (2008) Bilgen (2010) Kanyalkar and Gajendra (2010) Calvete et al. (2011) Liang (2011) Bashiri et al. (2012) Kopanos et al. (2012)	Chen and Wang (1997) Sakawa et al. (2001) Jackson and Grossmann (2003) Lababidi et al. (2004) Gen and Syarif (2005) Yılmaz and Çatay (2006) Ekşioğlu et al. (2007) Roghanian et al. (2007) Gunnarsson and Rönnqvist (2008) Ouhimmou et al. (2008) Alemany et al. (2010) Terrazas-Moreno and Grossmann (2011) Jayaraman and Pirkul (2001) Nikolopoulou and Ierapetritou (2012) Varthanan et al. (2012a)	Mohamed (1999) Jang et al. (2002) Alonso-Ayuso et al. (2003) Torabi and Hassini (2009) Lim et al. (2006) Ekşioğlu et al. (2006) Aliev et al. (2007) Gunnarsson et al. (2007) Selim et al. (2008) Liang and Cheng (2009) Peidro et al. (2010) Dhaenens-Flipo and Finke (2001) Peidro et al. (2011) Che (2012) Varthanan et al. (2012b)	Dogan and Goetschalckx (1999) Chen et al. (2003) Mohamed and Youseff (2004) Jolayemi and Olorunniwo (2004) Lei et al. (2006) Oh and Karimi (2006) Kanyalkar and Adil (2007) Lejeune and Ruszczyński (2007) Aydinel et al. (2008) Peidro et al. (2009a) Che and Chiang (2010) Torabi and Moghaddam (2011) Mirzapour Al-e-hashem et al. (2011) Liu and Papageorgiou (2012) Fahimnia et al. (2012)
Tactical production capacity expansion	Mohamed (1999) Yılmaz and Çatay (2006) Peidro et al. (2010) Liu and Papageorgiou (2012)	Chen et al. (2003) Genin et al. (2008) Torabi and Moghaddam (2011) Varthanan et al. (2012a)	Alonso-Ayuso et al. (2003) Selim et al. (2008) Liang (2011) Varthanan et al. (2012b)	Mohamed and Youseff (2004) Peidro et al. (2009a) Mirzapour Al-e-hashem et al. (2011) Bashiri et al. (2012)

Table 2 continued

Backlogging	McDonald and Karimi (1997) Gupta and Maranas (2003) Genin et al. (2008) Peidro et al. (2010) Peidro et al. (2011) Nikolopoulou and Ierapetritou (2012)	Gupta and Maranas (2000) Lababidi et al. (2004) Liang (2008) Fahimnia et al. (2012) Torabi and Moghaddam (2011)	Lee and Kim (2002) Park (2005) Peidro et al. (2009b) Liang (2011) Varthanan et al. (2012a)	Lee et al. (2002) Chern and Hsieh (2007) Alemany et al. (2010) Mirzapour Al-e-hashem et al. (2011) Varthanan et al. (2012b)
Distribution/logistics flexibility				
Multi-modal transport	Chen et al. (2003) Selim et al. (2008)	Lei et al. (2006) Gunnarsson and Rönnqvist (2008)	Lejeune (2006) Aydinel et al. (2008)	Gunnarsson et al. (2007)
Multi-carrier transport	Lei et al. (2006) Ouhimmou et al. (2008)	Yılmaz and Çatay (2006) Gunnarsson and Rönnqvist (2008)	Lejeune and Ruszczyński (2007) Aydinel et al. (2008)	Gunnarsson et al. (2007) Kopanos et al. (2012)
Multi-route transport	Sakawa et al. (2001) Lei et al. (2006) Aydinel et al. (2008) Calvete et al. (2011)	Lee et al. (2002) Lejeune and Ruszczyński (2007) Safaei et al. (2010) Fahimnia et al. (2012)	Lee and Kim (2002) Gunnarsson et al. (2007) Bilgen (2010)	Lababidi et al. (2004) Gunnarsson and Rönnqvist (2008) Armentano et al. (2011)
Tactical storage capacity expansion	Jolayemi and Olorunniwo (2004)	Bashiri et al. (2012)		

Table 3 Classification of the published models based on the integration of SCF options in different SC dimensions

Single-dimension flexibility (manufacturing only)	Multi-dimension flexibility		
	Sourcing and manufacturing	Manufacturing and distribution	Sourcing, manufacturing and distribution
McDonald and Karimi (1997)	Chen and Wang (1997)	Sakawa et al. (2001)	Jolayemi and Olorunniwo (2004)
Mohamed (1999)	Dogan and Goetschalckx (1999)	Lee et al. (2002)	Lejeune (2006)
Gupta and Maranas (2000)	Jayaraman and Pirkul (2001)	Lee and Kim (2002)	Yılmaz and Çatay (2006)
Dhaenens-Flipo and Finke (2001)	Jang et al. (2002)	Chen et al. (2003)	Lejeune and Ruszczyński (2007)
Jackson and Grossmann (2003)	Alonso-Ayuso et al. (2003)	Lababidi et al. (2004)	Gunnarsson et al. (2007)
Gupta and Maranas (2003)	Gen and Syarif (2005)	Lei et al. (2006)	Ouhimmou et al. (2008)
Souza et al. (2004)	Oh and Karimi (2006)	Selim et al. (2008)	Gunnarsson and Rönnqvist (2008)
Mohamed and Youseff (2004)	Lim et al. (2006)	Aydinel et al. (2008)	Fahimnia et al. (2012)
Park (2005)	Chern and Hsieh (2007)	Bilgen (2010)	Bashiri et al. (2012)
Ekşioğlu et al. (2006)	Tsai (2007)	Safaei et al. (2010)	
Kanyalkar and Adil (2007)	Meijboom and Obel (2007)	Armentano et al. (2011)	
Aliev et al. (2007)	Genin et al. (2008)	Calvete et al. (2011)	
Ekşioğlu et al. (2007)	Liang (2008)	Kopanos et al. (2012)	
Roghanian et al. (2007)	Peidro et al. (2009b)		
Kanyalkar and Gajendra (2010)	Torabi and Hassini (2009)		
Torabi and Moghaddam (2011)	Liang and Cheng (2009)		
Terrazas-Moreno and Grossmann (2011)	Peidro et al. (2010)		
Liu and Papageorgiou (2012)	Che and Chiang (2010)		
	Alemany et al. (2010)		
	Peidro et al. (2011)		
	Mirzapour Al-e-hashem et al. (2011)		
	Liang (2011)		
	Pal et al. (2011)		
	Che (2012)		
	Varthanan et al. (2012a)		
	Nikolopoulou and Ierapetritou (2012)		
	Varthanan et al. (2012b)		

decision making has become a key consideration in the more recent models, especially after 2004.

Overall, we see significant opportunities in SC distribution (external to the organization) opportunities for research. Modeling multi-modal transport research, in addition to capacity flexibility, have significant opportunity for expansion. Another issue with the lack of tactical planning is the possibility that many of the organizations that provide these external services may consider some of these tactical dimensions to be their strategic dimensions.

3.2 Classification based on the integration of SCF measures

In the previous section we made the observation that a number of publications may be grouped into multiple categories based on our general functional dimensions. This multidimensionality of modeling is an important issue. It is widely acknowledged that being flexible in one SC function does not guarantee an equivalent impact on the overall SCF and hence the flexibility-related decisions needs to consider the availability of flexibility

Table 4 Classification of the published models based on the solution methods used: exact methods

Model	Authors (year)	Solution method/Solver
Linear programming (LP)	Chen and Wang (1997)	IMSL package
	Mohamed (1999)	Not specified
	Lee and Kim (2002)	A hybrid simulation-analytic method
	Mohamed and Youseff (2004)	LINDO solver
	Oh and Karimi (2006)	CPLEX solver
	Genin et al. (2008)	CPLEX solver
Mixed Integer Linear Programming (MINLP)	McDonald and Karimi (1997)	CPLEX solver
	Dogan and Goetschalckx (1999)	CPLEX solver (a primal decomposition method)
	Dhaenens-Flipo and Finke (2001)	CPLEX solver
	Lee et al. (2002)	Hybrid analytic-simulation method
	Souza et al. (2004)	CPLEX solver
	Jolayemi and Olorunniwo (2004)	LINDO solver
	Lim et al. (2006)	MS Excel optimizer and simulation (IBM SCA)
	Meijboom and Obel (2007)	Simulation (OrgSim-system)
	Gunnarsson et al. (2007)	CPLEX solver
	Aydinel et al. (2008)	CPLEX solver
	Kanyalkar and Gajendra (2010)	Gnu Linear Programming Kit solver
	Safaei et al. (2010)	A hybrid mathematical–simulation method
	Alemany et al. (2010)	CPLEX solver
	Bashiri et al. (2012)	CPLEX solver
	Nikolopoulou and Ierapetritou (2012)	A hybrid mathematical-simulation method
	Kopanos et al. (2012)	CPLEX solver
	Liu and Papageorgiou (2012)	Multi-objective MILP solved using CPLEX (adopting ε-constraint and lexicographic minimax methods)

options in other SC processes (Gong 2008; Swafford et al. 2006; Stevenson and Spring 2007). In fact, it could be detrimental to organizations investing in flexibility of some functions without proper consideration of its impacts on the other SC processes and the overall SCF (Sawhney 2006). Based upon this viewpoint, we present a classification of the

Table 5 Classification of the published models based on the solution methods used: non-exact methods

Mathematical model	Solution approach	Authors (year)	Description
Linear models	Heuristics	Jayaraman and Pirkul (2001)	MILP model solved using Lagrangian relaxation techniques and a heuristic solution procedure
		Jang et al. (2002)	MILP model solved using Lagrangian heuristic and GA
		Park (2005)	MILP model solved using a heuristic based on local improvement procedure
		Gen and Syarif (2005)	MILP model solved using spanning tree-based hybrid GA and fuzzy techniques
		Lei et al. (2006)	MILP model solved using a two-phase approach (CPLEX + Load Consolidation heuristic)
		Ekşioğlu et al. (2006)	MILP model solved using primal–dual based heuristic
		Yılmaz and Çatay (2006)	MILP model solved using three linear relaxation based heuristics
		Ekşioğlu et al. (2007)	MILP model solved using a Lagrangean based decomposition heuristic
		Chern and Hsieh (2007)	Multi-objective LP model solved using a greedy algorithm
		Kanyalkar and Adil (2007)	MILP model solved using goal programming solved (weighted and pre-emptive methods)
		Gunnarsson and Rönnqvist (2008)	MILP model solved using a rolling planning horizon and Lagrangian decomposition/subgradient optimization
		Ouhimmou et al. (2008)	MILP model solved using a time decomposition approach
		Che and Chiang (2010)	MILP model solved using a GA based solution method
		Pal et al. (2011)	MILP model solved using an enhanced PSO and artificial bee colony
		Terrazas-Moreno and Grossmann (2011)	MILP model solved using two heuristics: a bi-level decomposition method and a hybrid decomposition method (combined bi-level and spatial Lagrangean decomposition methods)
		Armentano et al. (2011)	MILP model solved using two approaches: tabu search and an integrated path relinking/tabu search
		Varthanan et al. (2012a)	Multi-objective MILP model solved using analytic hierarchy process combined with PSO
		Varthanan et al. (2012b)	MILP model solved using simulation based PSO
	Meta-heuristics	Lejeune (2006)	MILP model solved using variable neighborhood decomposition search
		Aliev et al. (2007)	Fuzzy LP model solved using a GA based solution method
		Calvete et al. (2011)	Mixed-integer bi-level model solved using ant colony method
	Stochastic/probabilistic/fuzzy	Gupta and Maranas (2000)	Stochastic model converted to MINLP solved using outer approximation technique
		Sakawa et al. (2001)	MILP model with fuzzy goals and constraint solved using an LP solver
		Alonso-Ayuso et al. (2003)	An stochastic MILP model solved using Branch and Fix Coordination algorithm
		Gupta and Maranas (2003)	Stochastic model converted to MINLP solved using outer approximation technique
		Lababidi et al. (2004)	Stochastic linear model converted to MINLP solved by GAMS/XA solver
		Lejeune and Ruszczyński (2007)	Stochastic MILP model solved using a modular solution methodology

Table 5 continued

Mathematical model	Solution approach	Authors (year)	Description
		Roghanian et al. (2007)	Bi-level stochastic multi-objective LP model converted to a deterministic NLP solved using fuzzy goal programming (coded in LINGO)
		Selim et al. (2008)	Multi-objective LP model solved using fuzzy goal programming (coded in CPLEX)
		Liang (2008)	Fuzzy multi-objective LP model solved using goal programming (coded in LINGO)
		Torabi and Hassini (2009)	Possibilistic multi-objective MILP model solved using fuzzy goal programming (coded in GAMS/OSL)
		Peidro et al. (2009b)	Fuzzy MILP model converted to an equivalent crisp linear model using a linear ranking function, solved by CPLEX
		Liang and Cheng (2009)	Fuzzy multi-objective LP model solved using goal programming (coded in LINDO)
		Bilgen (2010)	Fuzzy MILP model converted to MILP using three different fuzzy operators (coded in CPLEX)
		Peidro et al. (2010)	Fuzzy MILP model solved using fuzzy goal programming (coded in CPLEX)
		Torabi and Moghaddam (2011)	Fuzzy multi-objective MILP model solved using fuzzy goal programming (coded in OSL)
		Peidro et al. (2011)	Fuzzy multi-objective LP model solved using fuzzy goal programming (coded in CPLEX)
		Liang (2011)	Fuzzy LP model solved using a heuristic fuzzy goal programming (coded in LINGO)
Nonlinear models	Heuristics	Jackson and Grossmann (2003)	NLP model solved using a Lagrangean based decomposition method
		Chen et al. (2003)	Multi-objective MINLP model solved using fuzzy goal programming approach in GAMS/SBB
		Tsai (2007)	MINLP model converted to an approximated MILP, solved by LINGO
		Mirzapour Al-e-hashem et al. (2011)	Multi-objective MINLP model converted to a multi-objective MILP, then to a single-objective model using LP-metrics method, solved using LINGO solver
		Che (2012)	MINLP model solved using a modified PSO
		Fahimnia et al. (2012)	MINLP model solved using a GA based solution method

modeling efforts concerning the integration of SCF options in single or multiple SC dimensions (Table 3).

Overall, despite the large percentage of papers having some integration, true broad-based integration across all functions and dimensions of the SC is relatively underrepresented. Also, most of the work is after 2004, further evidence that much of this research is in its relative infancy. An important observation is that in every single situation, the operations function is focused on manufacturing. Flexibility modeling in procurement and distribution processes has received relatively limited attention. This situation could be tied to flexibility emerging from the operations and manufacturing literature and then expanding to other SC functions over the years. For example, in the early to mid-1980's there was a significant growth in the study of advanced, flexible manufacturing systems (Narain et al. 2000).

Table 6 Classification of the published models based on the real world application

	Authors (year)	Case description
Automotive industry (component/part manufacturing)	Chen and Wang (1997)	Steel making company
	Dhaenens-Flipo and Finke (2001)	Metal items mass production
	Liang (2008)	Mechanical component manufacturer
	Genin et al. (2008)	Seamless steel tube manufacturer
	Liang and Cheng (2009)	Mechanical component manufacturer
	Torabi and Hassini (2009)	Automotive manufacturer
	Peidro et al. (2009b)	Automotive manufacturer
	Peidro et al. (2010)	Automotive manufacturer
	Liang (2011)	Mechanical component manufacturer
	Varthanan et al. (2012a)	Mechanical component manufacturer
	Varthanan et al. (2012b)	Mechanical component manufacturer
	Fahimnia et al. (2012)	Mechanical component manufacturer
Chemical industry	McDonald and Karimi (1997)	Chemical company
	Gupta and Maranas (2000)	Chemical company
	Lababidi et al. (2004)	Petrochemical company
	Lei et al. (2006)	Chemical company
	Lejeune (2006)	Chemical company
	Lejeune and Ruszczyński (2007)	Chemical company
	Terrazas-Moreno and Grossmann (2011)	Chemical company
	Liu and Papageorgiou (2012)	Agrochemical company
Wood & paper industry	Gunnarsson et al. (2007)	Pulp company
	Gunnarsson and Rönnqvist (2008)	Pulp company
	Aydinel et al. (2008)	Forest products company
	Mirzapour Al-e-hashem et al. (2011)	Wood and paper company
Others	Dogan and Goetschalckx (1999)	Cardboard package supplier
	Sakawa et al. (2001)	Housing material manufacturer
	Souza et al. (2004)	Electronics component manufacturing
	Kanyalkar and Adil (2007)	Unspecified customer goods company
	Meijboom and Obel (2007)	Pharmaceutical company
	Ouhimmou et al. (2008)	Furniture manufacturer
	Alemany et al. (2010)	Ceramic tile manufacturer
	Kanyalkar and Gajendra (2010)	Unspecified customer goods company
	Bilgen (2010)	Soft-drink producer
	Peidro et al. (2011)	Ceramic tile manufacturer
	Kopanos et al. (2012)	Dairy products producer

With a rapidly increasing rate of global sourcing and the growing significance of the procurement function (Benton 2010; Burke et al. 2007), the integration of manufacturing flexibility and sourcing flexibility has continued to rapidly evolve. This increased focus makes the integration of tactical flexibility research even more attractive.

Manufacturing and distribution flexibility integration modeling has a longer history than other integrative approaches. Whereas, SC planning models (in particular after 2006) tend to consider the integration of SCF-related decisions along the three SC dimensions (i.e.

sourcing, manufacturing and distribution). These observations all point to greater focus and need for research on the flexibility of non-manufacturing and broadly integrative tactical SCF analytical modeling.

3.3 Classification based on the solution methodology

Solution methodologies are important from a research perspective. Developments and application of specific types of methodologies is important since it not only provides resources on the type of methodologies that exist and can be applied to various settings, but it also identifies areas of methodologically oriented research. Of course, much of the type of solution methodology is based on model characteristics. Thus, we also classify the overall models into general linear and non-linear approaches. Further, we also break down the categories into exact, non-exact, heuristic and meta-heuristic approaches, as shown in Tables 4 and 5.

Only about a third of the solution methodologies can be classified as exact solution methods. Exact solution methods can be used to solve small/medium size linear, which could include mixed-integer-linear, problems. Due to the nature of SC planning problems, most of linear and nonlinear SC planning models are *mixed-integer* in form containing both continuous and binary (0-1) integer values. Some of this may be driven by the real world situations, but some may also be driven by the need for greater complexity in modeling to get published in leading journals. The same sort of pressure for identifying novel and innovative solution methods may be driven by publishing pressures, rather than practical applicability. In terms of solution tools and solvers, CPLEX has been the most popular linear solver that has been adopted to solve 52 % of all linear models.

Non-exact solution methods (including heuristics, meta-heuristics, stochastic, probabilistic, and fuzzy methods) have been used to deal with more complex, larger linear models as well as nonlinear models. Larger linear models (57 % of all published models) have resulted in unsolvable situations when using the exact solution techniques. Only 9 % of all modeling efforts have led to nonlinear models. Part of this may be driven by finding better and easier to solve optimization problems. The complexity of the modeling environment has led to the greater use of heuristic and meta-heuristic methods. There is a greater emphasis on heuristic approaches rather than broader meta-heuristic approaches. This situation admits the extreme complexity of most tactical SC planning problems requiring customized heuristics solution techniques instead of adopting off-the-shelf solution methods. More recently, there has been greater tendency towards the utilization of stochastic, probabilistic, and fuzzy modeling approaches to deal with SC uncertainty. About 25 % of all the published models use such techniques (17 studies out of a total of 67), all of which have been published during the past decade. Like any field, as the area advances greater complexity and more robust and powerful solution techniques replace older techniques. This is evident in the published works in the area of tactical SC optimization.

3.4 Classification based on practical application

Many of the characteristics of a model, and even solution methodology, may be dependent on the type of industry and product type studied, if there was a specific application. A classification based on the practical industrial application of the published models is shown in Table 6. First, we found that more than half of the reviewed articles have been applied or investigated practical industrial applications. The remaining publications focused on simulated numerical experiments. Almost three-quarters of the industrial application studies have been in three industries, including automotive, chemical, and wood and paper industry.

The results show a broad industry application over a number of different product types and families from durable discrete production goods to process oriented products. When considering the types of models used, most of the industries are looking for integrated functional perspectives. Interestingly, all the pulp and paper industry models included all three functional dimensions in their models. Thus, it can be expected that models that included practical applications tended to have more complex and comprehensive optimization models.

4 Conclusions and directions for further modeling efforts

In this paper, we provided an initial review of SC modeling research that has seen little investigation. Within SC design and planning, understanding of SCF is critical for competitive advantages as competition starts to shift to the SC versus SC level. Uncertainties and the growth of made-to-order (build) mass customization demands require a better understanding of SCF. SCF is an accepted, growing and important area of research as evidenced by the literature reviews covering this field. Our findings show that a large percentage of SC planning review papers mainly highlight the modeling characteristics and solution techniques without explicitly discussing the issue of flexibility (Comelli et al. 2008; Fahimnia et al. 2013a; Min and Zhou 2002; Mula et al. 2010; Peidro et al. 2009a; Schütz and Tomasgard 2011). The focus has been on strategic SCF with a greater emphasis on non-modeling studies (e.g. empirical field study oriented works).

Research on tactical SC planning can be explored to a larger extent if SCF can be appropriately defined and measured. However, a limited definition of SCF exists with confusion surrounding its scope and applicability (Sawhney 2006; Stevenson and Spring 2007; Swafford et al. 2006; Gong 2008). This is one of the contributions we sought to make in this paper by providing a review of formal analytical modeling approaches that covered some aspect of SCF across multiple dimensions of the SC.

A number of general observations provide insights into future research directions. One direction for future research may be to develop quantitative models that can examine the value of flexibility options in different SC dimensions and their interrelation (noting that flexibility does not come free). That is, the tradeoffs in other performance measures such as cost, quality and speed can be influenced by tactical SCF measures. Also, greater integrative measures which are evident in most practical settings are needed which may be developed and tested conceptually first. One thing we did find was that integrative models did not consider their own flexibility investigations. For example, analytical approaches can be used to investigate the effectiveness of incorporating multiple flexibility measures across SC and to show under what conditions one SCF measure can dominate another SCF measure. Comparative analyses across and between classifications (applications, functional integrative complexity, and solution methodology) can be investigated. We did see that research into some classifications, such as distribution and transportation, are underrepresented. Expanding many of the models from operations and manufacturing flexibility into these underrepresented areas of tactical flexibility research can be a fertile area for future research.

Although this study helps fill an important gap in the SC modeling research literature, it is not without limitations. These limitations provide fodder for additional investigation. We limited our search to actual published works in peer reviewed journals. We used the Scopus database for the search. Although a very comprehensive search engine, it doesn't cover all publishers and proceedings and research books that may contain some of the latest models. Also, research previous to 1996 may have fallen through the cracks, especially if electronic versions of the publications did not exist. A more exhaustive search could potentially provide a slight shift in our classifications. Another limitation of this review is that our SC functions were focused primarily on forward logistics. Our preliminary analysis on reverse logistics aspects of the SC shows that flexibility investigation in reverse SC operations is sparse. To the best of our knowledge, the only study that focuses on the development of a reverse logistics flexibility framework is the work of (Bai and Sarkis 2013) that attends to the strategic and operational flexibility options. A focus on tactical flexibility options and measures, especially analytical modeling, in a reverse SC is virtually non-existent in the current literature. Overall, SCF is a fertile area for research and we believe this paper helps set a foundation for additional understanding and research direction.

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