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Invited Review

Mathematical programming models for supply chain production and transport planning

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ABSTRACT

This paper presents a review of mathematical programming models for supply chain production and transport planning. The purpose of this review is to identify current and future research in this field and to propose a taxonomy framework based on the following elements: supply chain structure, decision level, modeling approach, purpose, shared information, limitations, novelty and application. The research objective is to provide readers with a starting point for mathematical modeling problems in supply chain production and transport planning aimed at production management researchers.

1. Introduction

A supply chain may be considered an integrated process in which a group of several organizations, such as suppliers, producers, distributors and retailers, work together to acquire raw materials with a view to converting them into end products which they distribute to retailers (Beamon, 1998). Simultaneously considering supply chain production and transport planning problems greatly advances the efficiency of both processes. The literature in the field is vast, so an extensive review of existing research on the topic is presented in an attempt to gain a better understanding of the mathematical modeling methods used in supply chain production and transport planning, and to provide a basis for future research. Given the globalization of operations, new models and tools for improving the forecasting, replenishment and production plans along supply chains are required. Furthermore in the context of supply chains, manufacturing companies increasingly need to integrate production and transport planning in order to optimize both these processes simultaneously.

In general, we have selected papers based on the following main criteria to be included in this survey: (i) mathematical programming models, and (ii) centralized planning models. This review does not include those works which focus on the operational decision levels and cover themes like lot sizing or production sequencing. However, those works presenting production planning models which consider transport a resource to distribute products, and focus on the tactical and/or operational levels and their possible combinations with aspects of a strategical nature, are considered in this review.

We briefly describe each paper, but we do not describe or formulate the models that have been considered in detail. This work neither intends to identify every bibliographic work nor to extend a review of them, but to provide the reader with a starting point to investigate the literature about the best management methods for different supply chain production and transport planning problems. The objective of this paper is to (i) review the literature, (ii) classify the literature based on the supply chain structure, decision level, modeling approach, purpose, shared information, limitations, novelty and application; and, (iii) identify future research directions. This work can act as an overview of the state of the art of mathematical programming models for supply chain production and transport planning for new supply chain planning researchers. Besides, it can help practitioners to address this type of real-world problems in supply chains.

The remainder of the paper consists of three other sections. The next section introduces the review methodology. Then Section 3 presents the taxonomy of the reviewed papers. Finally, the last section provides the conclusions and directions for future research.

2. Review methodology

The search process was carried out with scientific-technical bibliographic databases which include publishing portals like Elsevier, Taylor & Francis, Wiley or Emerald. The following search criteria were applied: supply chain linear programming models, supply

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chain production and transport planning, supply chain centralized planning models, supply chain production and distribution planning, nonlinear programming of production and distribution planning, and multi-objective programming of production and distribution planning. Furthermore, the bibliographic references of the articles studied have served as a continuous search reference. Thus, although we did not initially include mixed integer programming as a search criteria, many of the applications referred to were mixed integer programming models.

Firstly, 127 references were collected for the study with a time frame of 25 years. Two groups may be distinguished in these reviewed works; on the one hand, review articles in which different supply chain planning models with a range of criteria while, on the other hand, articles that propose different mathematical programming types for supply chain production and transport planning. Regarding the former group of works, those of Vidal and Goetschalckx (1997), Beamon (1998), Erenguc et al. (1999), Schmidt and Wilhelm (2000), Bilgen and Ozkarahan (2004), Shah (2005), Stadtler (2005) and Dullaert et al. (2007) stand out. Of the latter group, we excluded those articles whose mathematical models centered exclusively on the strategic decision level and on themes such as the supply network design, and the location of production or distribution centers. Likewise, those works focusing on the operational decision level and on themes such as lot sizing or production sequencing were also ruled out. Therefore works presenting supply chain production planning models considering transport as a product distribution resource, those that center on tactical and/or operational decision levels and their possible combination with aspects of a strategic nature, were considered. After this process, a total of 44 references were selected. These references were obtained from journals (93.18%) and congresses (6.82%). One group of six journals represented 48.84% of all the references included in this work, these being: European Journal of Operational Research, Computers and Chemical Engineering, Computers and Industrial Engineering, Computers and Operations Research, IIE Transactions, Industrial and Engineering Chemistry Research (Table 1).

Nonetheless, we did not take into account the commercial software offered by i2, ILOG, Optiant and other companies for supply chain network optimization. This is understandable given the dearth of published papers about applications with these systems.

Table 1
Distribution of references according to journals.

Journal	References	% Total
European Journal of Operational Research	5	11.36
Computers and Chemical Engineering	4	9.09
Computers and Industrial Engineering,	3	6.82
Computers and Operations Research	3	6.82
IIE Transactions	3	6.82
Industrial and Engineering Chemistry Research	3	6.82
International Journal of Production Economics	2	4.55
Omega-International Journal of Management Science	2	4.55
International Journal of Production Research	2	4.55
Interfaces	2	4.55
AICHE Journal	1	2.27
Applied Mathematics and Computation	1	2.27
Expert Systems with Applications	1	2.27
Fuzzy Sets and Systems	1	2.27
Information Sciences	1	2.27
International Journal of Advanced Manufacturing Technology	1	2.27
Or Spectrum	1	2.27
Proceedings of the 2000 Winter Simulation Conference	1	2.27
Proceedings of the 35th Annual Hawaii International Conference on System Sciences	1	2.27
Production Planning and Control	1	2.27
Transportation Research Part E-Logistics and Transportation Review	1	2.27
Transportation Science	1	2.27
International Journal of Operations and Production Management	1	2.27
Journal of the Operational Research Society	1	2.27
Annual meeting of the North American Fuzzy Information Processing Society 2006	1	2.27
Total	44	100.00

3. Taxonomy

Huang et al. (2003) studied the shared information of supply chain production. They considered and proposed four classification criteria: supply chain structure, decision level, modeling approach and shared information. We have expanded Huang's taxonomy by adding four additional criteria: purpose, limitations, novelty and practical application. All of them are briefly described below:

Supply chain structure: It defines the way that the various organizations within the supply chain are arranged and how they relate to each other.

Decision level: Three decision levels may be distinguished in terms of the decision to be made; strategic, tactical and operational; and its corresponding period, i.e., long term, mid term and short term.

Supply chain analytical modeling approach: This approach consists in the type of representation, in this case, relationship mathematics, and the aspects to be considered in the supply chain.

Purpose: This/these is/are the objective/s defined in the mathematical model.

Shared information: This consists in the information shared between each network node that the model determines, and which enables production and transport planning in accordance with the purpose drawn up.

Limitations: Identification of those characteristics which limit the model from being applied to certain environments.

Novelty: Establish the authors' contribution in relation to the rest of the scientific literature.

Practical application: This presents the application that each model considers in terms of supporting practical or case studies.

Fig. 1 interrelates the previously described classification criteria. First of all, the horizon for which planning was carried out is contemplated and, therefore, the corresponding decision level. Having determined this horizon, the aspects related to both the mathematical modeling approach and the structure of the application framework are dealt with. Next, the function(s), objective(s) or purpose(s) along with the relevant information exchange by means of the mathematical model's parameters are analyzed. Furthermore, the aspects of the framework determined by the supply chain structure are considered which, on occasion, determine the model's possible limitations and the type of information being exchanged among the various nodes. Likewise, special attention is paid to applying the models to real cases. Finally, the contribution or novelty that the models offers are analyzed because they may relate to both the corresponding aspects of the model and those that consider the factors of the framework.

3.1. Supply chain structure

Beamon and Chen (2001) classified the supply chain structure into four main types:

Convergent: each node in the chain has one successor at least, and several predecessors.

Divergent: each node has one predecessor, at least, and several successors.

Conjoined: a combination of each convergent chain and one divergent chain.

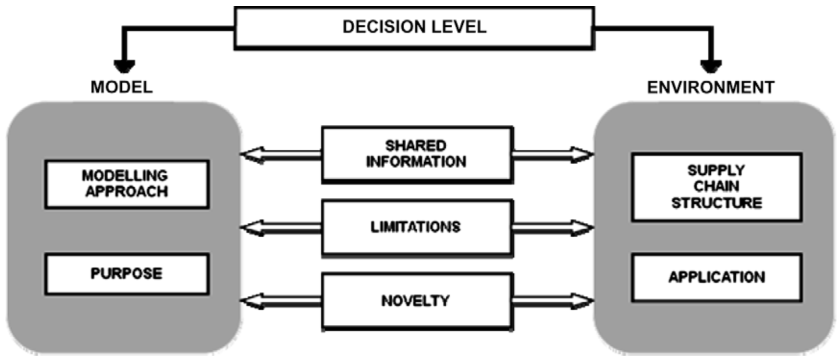

Fig. 1. Taxonomy criteria.

Table 2
Decision level of reviewed works.

Author	Strategical	Tactical	Operational
Benjamin (1989)		X	
Martin et al. (1993)		X	
Chen and Wang (1997)		X	
Mcdonald and Karimi (1997)		X	
Barbarosoğlu and Ozgur (1999)		X	
Dogan and Goetschalckx (1999)	X	X	
Lee and Kim (2000)		X	
Sabri and Beamon (2000)	X		X
Timpe and Kallrath (2000)	X		X
Dhaenens-flipo and Finke (2001)		X	
Jayaraman and Pirkul (2001)	X	X	
Sakawa et al. (2001)		X	
Bredstrom and Ronnqvist (2002)		X	X
Goetschalckx et al. (2002)	X	X	
Jang et al. (2002)	X	X	
Kallrath (2002)	X		X
Lee et al. (2002)		X	
Lee and Kim (2002)		X	
Chen et al. (2003)		X	
Gupta and Maranas (2003)		X	
Perea-lopez et al. (2003)		X	
Chen and Lee (2004)		X	
Lababidi et al. (2004)		X	
Ryu et al. (2004)		X	
Gen and Syarif (2005)		X	
Kanyalkar and Adil (2005)		X	X
Park (2005)		X	
Demirli and Yimer (2006)		X	
Ekşioğlu et al. (2006)		X	
Lim et al. (2006)		X	
Oh and Karimi (2006)		X	
Rizk et al. (2006)			X
Aliev et al. (2007)		X	
Bilgen and Ozkarahan (2007)		X	
Chern and Hsieh (2007)		X	
Ekşioğlu et al. (2007)		X	
Meijboom and Obel (2007)		X	
Roghanian et al. (2007)		X	
Jung et al. (2008)		X	
Liang and Cheng (2008)		X	
Rizk et al. (2008)			X
Selim et al. (2008)		X	
Torabi and Hassini (2008)		X	
Romo et al. (2009)		X	X

Network: this cannot be classified as convergent, divergent or conjoined, and is more complex than the three previous types.

With regard to the reviewed works, the vast majority presents a network-like structure, and mainly combines the presence of manufacturing and distribution centers, and sometimes add suppliers and/or retailers as supply chain links. Only five references consider a single production center and present structures of either a divergent type (Barbarosoğlu and Ozgur, 1999; Rizk et al., 2006, 2008) or a conjoined kind (Demirli and Yimer, 2006; Torabi and Hassini, 2008). Some of the industrial sectors they include are glass, steel, chemical, paper pulp, petrochemical and cereals.

3.2. Decision level

Decision levels are mainly classified by the extent or effect of the decision to be made in terms of time. For instance at the strategical level, Huang et al. (2003) identified the decisions made in relation to selecting production, storage and distribution locations, and they also considered subcontracting part of production to minimize overall costs. At the tactical level however, they identified aspects such as production and distribution planning, assigning production and transport capacities, inventories and managing safety inventories. Finally at the operational level, they classified replenishment and delivery operations. Table 2 classifies the works reviewed in terms of the decision level considered.

All but five of the reviewed works focus on the tactical decision level (Sabri and Beamon, 2000; Timpe and Kallrath, 2000; Kallrath, 2002; Rizk et al., 2006, 2008). Of this group of works, only Rizk et al. (2006, 2008) cover the operational decision level exclusively, whereas the other works combine the strategical and operational levels. Furthermore, another group of four references emerges (Dogan and Goetschalckx, 1999; Jayaraman and Pirkul, 2001; Goetschalckx et al., 2002; Jang et al., 2002) which simultaneously consider aspects related to the strategical and tactical levels. It should be stressed that the strategical aspects covered mainly refer to the supply chain design, except that proposed by Timpe and Kallrath (2000) which centers more on business aspects.

3.3. Modeling approach

The vast majority of the works reviewed opt for the linear programming-based modeling approach, particularly mixed integer linear programming models (see Table 4). Conversely, nonlinear programming is only used in two references (Benjamin, 1989; Lababidi et al., 2004). Six references refer to the multi-objective programming-based modeling approach, of which three use either multi-objective linear or integer linear multi-objective programming, while the other three opt for nonlinear modeling. The inclusion of uncertainty in the various models is achieved by fuzzy programming with stochastic programming. Both kinds of mathematical programming appear as either a complementary modeling approach or the main approach as in Sakawa et al. (2001), Demirli and Yimer (2006) and Aliev et al. (2007) for fuzzy programming, or as in Sabri and Beamon (2000) and Goetschalckx et al. (2002) for stochastic programming. Likewise, heuristic solution algorithms and metaheuristics are used as complementary techniques to solve mathematical programming models, mainly integer linear programming and, to a lesser extent, nonlinear, multi-objective or fuzzy programming. The use of simulation tools to complement the mathematical models is considered in the hybrid modeling approach referred to in four references (Lee and Kim, 2000, 2002; Lee et al., 2002; Lim et al., 2006).

Next, the details of each modeling approach used by the different works reviewed are provided.

Table 3
Modeling approach codes.

Modeling approach	Detail	Code
Linear programming	Linear programming	LP
	Mixed integer/Integer linear programming	ILP
Non linear programming	Non linear programming	NLP
	Mixed integer/Integer non linear programming	INLP
Multi-objective programming	Multi-objective linear programming	MOLP
	Multi-objective integer linear programming	MOILP
	Multi-objective non linear programming	MONLP
	Multi-objective non linear integer programming	MONLIP
Fuzzy programming	Fuzzy mathematical programming	FMP
Stochastic programming	Stochastic programming	SP
Heurístics algorithms and metaheurístics	Heurístics algorithms and metaheurístics	HEU
Hybrid models	Hybrid models	HYB

3.3.1. Linear programming

Martin et al. (1993) presented a linear programming model for planning production, distribution and inventory operations in the glass sector industry. Chen and Wang (1997) proposed a linear programming model to solve integrated supply, production and distribution planning in a supply chain of the steel sector. Ryu et al. (2004) suggested a bi-level modeling approach comprising two linear programming models, one for production planning and one for distribution planning. These models subsequently consider demand uncertainty, resources and capacities when they are reformulated by multi-parametric linear programming. Kanyalkar and Adil (2005) proposed a linear programming model for aggregated and detailed production and dynamic distribution planning in a multiproduct and multiplant supply chain. Oh and Karimi (2006) put forward a linear programming model that integrates production and distribution planning for a multinational firm in the chemical sector in a multi-plant, multi-period and multi-product environment. This model also works with tax and financial data, such as taxes related with the firm's business activity or amortiza-

Table 4
Modeling approach of the reviewed works.

Author	LP	ILP	NLP	INLP	MOLP	MOILP	MONLP	MONLIP	FMP	SP	HEU	HYB
Benjamin (1989)			X								X	
Martin et al. (1993)	X											
Chen and Wang (1997)	X											
Mcdonald and Karimi (1997)		X										
Barbarosoğlu and Ozgur (1999)		X										
Dogan and Goetschalckx (1999)		X										
Lee and Kim (2000)												X
Sabri and Beamon (2000)										X		
Timpe and Kallrath (2000)		X										
Dhaenens-flipo and Finke (2001)		X										
Jayaraman and Pirkul (2001)		X									X	
Sakawa et al. (2001)									X			
Bredstrom and Ronnqvist (2002)		X										
Goetschalckx et al. (2002)		X									X	
Jang et al. (2002)		X									X	
Kallrath (2002)		X										
Lee et al. (2002)												X
Lee and Kim (2002)												X
Chen et al. (2003)								X				
Gupta and Maranas (2003)										X		
Perea-lopez et al. (2003)		X										
Chen and Lee (2004)								X				
Lababidi et al. (2004)				X						X		
Ryu et al. (2004)	X											
Gen and Syarif (2005)		X							X		X	
Kanyalkar and Adil (2005)	X											
Park (2005)		X									X	
Demirli and Yimer (2006)									X			
Ekşioğlu et al. (2006)		X									X	
Lim et al. (2006)												X
Oh and Karimi (2006)	X											
Rizk et al. (2006)		X										
Aliev et al. (2007)									X		X	
Bilgen and Ozkarahan (2007)		X										
Chern and Hsieh (2007)					X						X	
Ekşioğlu et al. (2007)		X										
Meijboom and Obel (2007)		X										
Roghanian et al. (2007)							X		X	X		
Jung et al. (2008)	X											
Liang and Cheng (2008)									X			
Rizk et al. (2008)		X									X	
Selim et al. (2008)					X				X			
Torabi and Hassini (2008)						X			X			
Romo et al. (2009)		X										

Table 5
Purpose of the reviewed works.

Author	Costs			Customer				Inventories
	MC	MR	MB	MSL	MBA	F	FW	MSI
Benjamin (1989)	**X**							
Martin et al. (1993)			X					
Chen and Wang (1997)			X					
Mcdonald and Karimi (1997)			X					
Barbarosoğlu and Ozgur (1999)	X							
Dogan and Goetschalckx (1999)	X							
Lee and Kim (2000)	X							
Sabri and Beamon (2000)	X					X		
Timpe and Kallrath (2000)		X	X					
Dhaenens-flipo and Finke (2001)	X							
Jayaraman and Pirkul (2001)	X							
Sakawa et al. (2001)	X							
Bredstrom and Ronnqvist (2002)	X							
Goetschalckx et al. (2002)	X							
Jang et al. (2002)	X							
Kallrath (2002)	X	X	X					
Lee et al. (2002)	X							
Lee and Kim (2002)	X							
Chen et al. (2003)			X	X				X
Gupta and Maranas (2003)	X							
Perea-lopez et al. (2003)			X					
Chen and Lee (2004)			X	X				X
Lababidi et al. (2004)	X							
Ryu et al. (2004)	X							
Gen and Syarif (2005)	X							
Kanyalkar and Adil (2005)	X							
Park (2005)			X					
Demirli and Yimer (2006)	X							
Ekşioğlu et al. (2006)	X							
Lim et al. (2006)	X							
Oh and Karimi (2006)			X					
Rizk et al. (2006)	X							
Aliev et al. (2007)			X	X				
Bilgen and Ozkarahan (2007)	X							
Chern and Hsieh (2007)	X							
Ekşioğlu et al. (2007)	X							
Meijboom and Obel (2007)			X					
Roghanian et al. (2007)	X							
Jung et al. (2008)			X					
Liang and Cheng (2008)	X				X			
Rizk et al. (2008)	X							
Selim et al. (2008)	X		X	X				
Torabi and Hassini (2008)	X			X				
Romo et al. (2009)							X	

Table 6
Shared information codes.

Type	Information	Code
Product	Product structure	PS
Process	Lead time	LT
	Production cost	PC
	Transport time	TT
	Transport cost	TC
	Set-up time	ST
	Set-up cost	SC
	Outsourcing cost	OC
	Replenishment cost	RC
	Revenues/benefits	R
Inventory	Inventory levels	IL
	Inventory costs	IC
	Backorder costs	BC
	Service level/flexibility	SL
Resources	Production capacity	PCA
	Transport capacity	TCA
	Holding capacity	HCA
	Replenishment capacity	RCA
Orders	Flexibility (volume or due date)	F
	Order limit date	OLD
Planning	Demand	D

tions. Jung et al. (2008) compared linear programming models for centralized and decentralized production and transport planning environments.

3.3.2. Mixed integer/integer linear programming

Mcdonald and Karimi (1997) presented a mixed deterministic integer linear programming model to solve a production and transport planning problem in the chemical industry in a multi-plant, multi-product and multi-period environment. Barbarosoğlu and Ozgur (1999) developed a mixed integer linear programming model which is solved by Lagrangian and heuristic relaxation techniques to become a decentralized two-stage model: one for production planning and another for transport planning. On the other hand, Dogan and Goetschalckx (1999) proposed a mixed integer linear programming model for designing supply chain production and distribution planning. Goetschalckx et al. (2002) presented two mixed integer linear programming models, one for the supply chain design phase and the other for production planning, inventory planning and national supply chain transport planning with seasonal demand. Timpe and Kallrath (2000) and Kallrath (2002) presented a mixed integer linear programming model for production, distribution and sales planning with

Table 7a
Shared process information of the reviewed works.

Author	Shared process information								
	Lead time	Production cost	Transport time	Transport cost	Set-up time	Set-up cost	Outsourcing cost	Replenishment cost	Revenues/ benefit
Benjamin (1989)		X		X		X		X	
Martin et al. (1993)		X							X
Chen and Wang (1997)		X		X				X	
Mcdonald and Karimi (1997)		X		X				X	X
Barbarosoğlu and Ozgur (1999)	X	X		X					
Dogan and Goetschalckx (1999)		X	X	X				X	X
Lee and Kim (2000)	X	X	X	X				X	
Sabri and Beamon (2000)	X	X		X	X	X		X	
Timpe and Kallrath (2000)		X	X	X		X		X	
Dhaenens-flipo and Finke (2001)	X	X		X	X				
Jayaraman and Pirkul (2001)		X		X				X	
Sakawa et al. (2001)		X		X					
Bredstrom and Ronnqvist (2002)		X		X					
Goetschalckx et al. (2002)		X	X	X				X	X
Jang et al. (2002)	X	X		X					
Kallrath (2002)		X	X	X		X		X	
Lee et al. (2002)	X	X	X	X					
Lee and Kim (2002)	X	X	X	X					
Chen et al. (2003)		X	X	X		X			X
Gupta and Maranas (2003)	X	X		X				X	X
Perea-lopez et al. (2003)	X	X	X	X		X		X	X
Chen and Lee (2004)		X	X	X		X			
Lababidi et al. (2004)		X		X				X	X
Ryu et al. (2004)		X		X					
Gen and Syarif (2005)		X		X					
Kanyalkar and Adil (2005)				X					
Park (2005)		X		X		X			
Demirli and Yimer (2006)		X		X				X	
Ekşioğlu et al. (2006)		X		X		X			
Lim et al. (2006)	X	X		X					
Oh and Karimi (2006)		X		X			X		X
Rizk et al. (2006)	X		X	X	X	X			
Aliev et al. (2007)		X		X					
Bilgen and Ozkarahan (2007)		X		X					
Chern and Hsieh (2007)	X	X	X	X			X		
Ekşioğlu et al. (2007)		X		X		X			
Meijboom and Obel (2007)		X						X	X
Roghanian et al. (2007)		X		X					
Jung et al. (2008)		X		X					X
Liang and Cheng (2008)	X		X				X		
Rizk et al. (2008)	X		X	X	X	X			
Selim et al. (2008)	X	X		X					X
Torabi and Hassini (2008)		X		X				X	
Romo et al. (2009)									

different time scales for business and production aspects. Dhaenens-flipo and Finke (2001) developed a mixed integer linear programming-based planning model in a multi-firm, multi-product and multi-period environment. Jayaraman and Pirkul (2001) put forward an integrated model for supply chain design and planning by means of mixed integer linear programming. Sakawa et al. (2001) elaborated a mixed integer linear programming model for production and transport planning in a Japanese firm that produces construction elements. On the other hand, Bredstrom and Ronnqvist (2002) considered two independent mixed integer linear programming models, one for production planning which considers transport costs, and the other for distribution planning in a multi-period and multi-product environment. Jang et al. (2002) developed a system with four modules for supply chain management, these being supply chain design, production and distribution planning, the model management module and the data processing module. The supply chain design and the production planning models, which have several supply tiers in relation to the list of materials, and transport, are formulated by mixed integer linear programming. Perea-lopez et al. (2003) developed a multi-period mixed integer linear programming model for supply chain dynamical characterization. The use of a predictive control model complements this model. Gen and Syarif (2005) elaborated a mixed integer linear programming model for production and transport planning solved by genetic algorithms and fuzzy techniques. Park (2005) suggested an integrated transport and production planning model that uses mixed integer linear programming in a multi-site, multi-retailer, multi-product and multi-period environment. Likewise, the author also presented a production planning submodel whose outputs act as the input in another submodel with a transport planning purpose and an overall objective of maximizing overall profits with the same technique. Ekşioğlu et al. (2006) showed an integrated transport and production planning model in a multi-period, multi-site, monoproduct environment as a flow or graph network to which the authors added a mixed integer linear programming formulation. Later, Ekşioğlu et al. (2007) extended this model to become a multi-product model solved by Lagrangian decomposition. Rizk et al. (2006) suggested a mixed integer linear programming model for the production process along with three different piecewise linear functions used to develop three equivalent mixed integer linear programming models for the distribution process in which scale economies are contemplated. Bilgen and Ozkarahan (2007) considered a model that integrates mixes, loads and transport between various sea ports used

Table 7b
Shared product, inventory and resources information of the reviewed works.

Author	Product	Inventory				Resources			
	Product structure	Inventory levels	Inventory cost	Backorder cost	Service level/ flexibility	Production capacity	Transport capacity	Holding capacity	Replenishment capacity
Benjamin (1989)			X						
Martin et al. (1993)		X	X	X				X	
Chen and Wang (1997)	X					X			X
Mcdonald and Karimi (1997)		X	X	X		X			
Barbarosoğlu and Ozgur (1999)			X			X			
Dogan and Goetschalckx (1999)			X			X		X	X
Lee and Kim (2000)	X	X	X	X		X	X	X	
Sabri and Beamon (2000)	X		X	X	X	X		X	
Timpe and Kallrath (2000)	X	X	X			X		X	X
Dhaenens-flipo and Finke (2001)		X	X			X			
Jayaraman and Pirkul (2001)	X					X			X
Sakawa et al. (2001)						X			
Bredstrom and Ronnqvist (2002)	X	X	X			X	X		
Goetschalckx et al. (2002)			X			X	X	X	X
Jang et al. (2002)	X		X			X			
Kallrath (2002)	X	X	X			X			X
Lee et al. (2002)	X	X	X	X				X	
Lee and Kim (2002)	X	X	X	X		X	X		
Chen et al. (2003)		X	X				X	X	
Gupta and Maranas (2003)		X	X			X			
Perea-lopez et al. (2003)		X	X						
Chen and Lee (2004)		X	X				X	X	
Lababidi et al. (2004)	X		X	X		X		X	
Ryu et al. (2004)			X			X		X	
Gen and Syarif (2005)	X		X			X			
Kanyalkar and Adil (2005)	X	X	X			X		X	
Park (2005)				X		X		X	
Demirli and Yimer (2006)	X	X	X	X	X	X	X	X	
Ekşioğlu et al. (2006)			X			X	X		
Lim et al. (2006)	X		X			X			
Oh and Karimi (2006)	X		X			X	X	X	X
Rizk et al. (2006)	X		X			X			
Aliev et al. (2007)		X	X			X		X	
Bilgen and Ozkarahan (2007)	X		X			X	X	X	
Chern and Hsieh (2007)	X		X	X		X	X		
Ekşioğlu et al. (2007)			X			X			
Meijboom and Obel (2007)	X					X			
Roghanian et al. (2007)			X			X			
Jung et al. (2008)			X			X		X	
Liang and Cheng (2008)								X	
Rizk et al. (2008)	X		X			X	X		
Selim et al. (2008)			X			X	X	X	
Torabi and Hassini (2008)	X	X	X			X		X	X
Romo et al. (2009)	X					X	X		

in the cereal industry by means of mixed integer lineal programming in a multi-period environment. Meijboom and Obel (2007) developed a mixed integer linear programming model for mid-term planning. The authors also studied the coordination between the various stages of a supply chain. Rizk et al. (2008) suggested a mixed integer linear programming model for production and distribution planning in a production environment with a single production plant and several distribution centers. Romo et al. (2009) implemented a model for optimizing Norwegian natural gas production and transport in a mixed-integer linear programming context.

3.3.3. Non linear programming

Benjamin (1989) proposed a nonlinear programming model which is solved by the gradient algorithm complemented by a heuristic algorithm. Lababidi et al. (2004) developed a deterministic mixed integer nonlinear programming model to optimize the supply chain of a petrochemical company.

3.3.4. Multi-objective programming

Chen et al. (2003) presented a model that was formulated by mixed integer nonlinear multi-objective programming for a multi-product, multi-period and multi-plant environment which may use scale economies. Also, Chen and Lee (2004) proposed a multi-objective mixed integer nonlinear programming model which considers uncertainty for demand and prices, and models according to the production, transport, sales and inventory planning stages. Chern and Hsieh (2007) proposed a multi-objective linear programming model for master production planning. Selim et al. (2008) proposes a multi-objective linear programming model for collaborative production and distribution planning. Besides, Torabi and Hassini (2008) presented a positive multi-objective linear programming model for master supply chain production planning.

3.3.5. Fuzzy mathematical programming

Sakawa et al. (2001) include uncertainty in some of their model's parameters by using fuzzy mathematical programming. Demirli and Yimer (2006) presented a fuzzy mixed integer programming model for integrated production and distribution planning in a built-to-order production supply chain. Aliev et al. (2007) presented an integrated fuzzy linear programming model for multi-product and multi-period production and distribution planning. Both the objective function of the model and the decision variables are considered to be fuzzy. Liang and Cheng (2008) proposed a fuzzy multi-objective linear programming model by considering uncertainty in terms of demand and capacity in a multi-period and multi-product environment for a firm that produces mechanical elements. Selim et al. (2008) includes uncertainty in their proposed model adopting a programming approach based on fuzzy objectives.

Table 7c
Shared orders and planning information of the reviewed works.

Author	Orders		Planning
	Flexibility (volume or due date)	Order limit date	Demand
Benjamin (1989)			
Martin et al. (1993)			X
Chen and Wang (1997)			X
Mcdonald and Karimi (1997)			X
Barbarosoğlu and Ozgur (1999)			X
Dogan and Goetschalckx (1999)			X
Lee and Kim (2000)			X
Sabri and Beamon (2000)	X		X
Timpe and Kallrath (2000)			X
Dhaenens-flipo and Finke (2001)			
Jayaraman and Pirkul (2001)			X
Sakawa et al. (2001)			X
Bredstrom and Ronnqvist (2002)			X
Goetschalckx et al. (2002)			X
Jang et al. (2002)			X
Kallrath (2002)			X
Lee et al. (2002)			X
Lee and Kim (2002)			X
Chen et al. (2003)			X
Gupta and Maranas (2003)			X
Perea-lopez et al. (2003)			X
Chen and Lee (2004)			X
Lababidi et al. (2004)			X
Ryu et al. (2004)			X
Gen and Syarif (2005)			X
Kanyalkar and Adil (2005)			X
Park (2005)			X
Demirli and Yimer (2006)			X
Ekşioğlu et al. (2006)			X
Lim et al. (2006)			X
Oh and Karimi (2006)			X
Rizk et al. (2006)			X
Aliev et al. (2007)			X
Bilgen and Ozkarahan (2007)			X
Chern and Hsieh (2007)		X	X
Ekşioğlu et al. (2007)			X
Meijboom and Obel (2007)			X
Roghanian et al. (2007)			X
Jung et al. (2008)			X
Liang and Cheng (2008)			
Rizk et al. (2008)			X
Selim et al. (2008)			X
Torabi and Hassini (2008)			X
Romo et al. (2009)			X

Table 8
Limitation codes.

Type	Limitation	Code
Supply chain structure	Suppliers are not considered	SNC
	Distribution centers are not considered	DNC
	Retailers are not considered	RNC
Data	Set-up time is not considered	STNC
	Lead time is not considered	LTNC
	Production capacity is infinite	PCI
	Transport capacity is infinite	TCI
	Holding capacity or raw materials availability is infinite	HCI
Demand	Backorder demand is not allowed	BDNA

3.3.6. Stochastic programming

Sabri and Beamon (2000) put forward a multi-objective stochastic model for strategical and operative planning in supply chains. The outputs of the strategical submodel act as the inputs of the operational submodel, which incorporates demand uncertainty, of production and distribution, whose results once again feedback the strategical submodel in an iterative process. Gupta and Maranas (2003) adopted McDonald and Karimi's model (1997) as the basis of their work, and proposed transformation in a stochastic model which considers demand uncertainty. Lababidi et al. (2004) include uncertainty with a two-stage stochastic programming model. Roghanian et al. (2007) presented a bi-level stochastic modeling approach with multi-objective linear programming, one level for production planning and another for distribution planning. This model is solved by transforming the bi-level stochastic model into an equivalent deterministic model with multi-objective nonlinear programming to which fuzzy techniques are applied to solve it.

3.3.7. Heuristics algorithms and metaheuristics

Both models proposed by Goetschalckx et al. (2002) are solved with heuristic techniques. Also, the integrated model developed by Jayaraman and Pirkul (2001) is solved by Lagrangian relaxation techniques and by heuristic solution processes. The design and production planning proposed by Jang et al. (2002) are solved by Lagrangian relaxation techniques and genetic algorithms. The mixed integer linear programming model developed by Gen and Syarif (2005) is solved by genetic algorithms and fuzzy techniques. Park (2005) proposes a two-phase heuristic model to solve his production and distribution planning model. The first stage establishes an initial distribution and production plan, which is improved in the second phase by modifying the transport parameters. Ekşioğlu et al. (2006) reformulated their model by relaxation techniques and solved it by applying a primal–dual heuristic algorithm. The fuzzy model proposed by Aliev et al. (2007) is solved by a genetic algorithm, like the master planning model proposed by Chern and Hsieh (2007).

3.3.8. Hybrid models

Lee and Kim (2000, 2002) and Lee et al. (2002) proposed a hybrid model that combines linear programming and simulation by adapting the total system capacity in a multi-product, multi-period and multi-plant environment. Also, Lim et al. (2006) presented a hybrid model formed not only by a mixed integer linear programming model for the production and storage capacities decision making of each link of the chain, but also by a discrete simulation model of events for production and distribution planning.

Table 3 provides the various types of modeling approach used in the works reviewed and Table 4 groups the reviewed works by the modeling approach they employ.

3.4. Purposes

These are considered quantitative aspects related to costs, customer service and inventories. Regarding costs, the minimization of costs (MC), the maximization of revenues (MR) and the maximization of benefit (MB) are contemplated, while the maximization of the service level (MSL), the minimization of backorders (MBA), the flexibility in volume or delivery dates (F) or the maximization of flow (FW) are considered for customer services. The maximization of safety inventories is also taken into account (MSI). Table 5 classifies the works reviewed in terms of the purpose considered.

Minimization of total costs is the main purpose of the works reviewed, while maximization of revenues or sales is considered to a lesser extent. Besides, works like those of Selim et al. (2008) simultaneously consider minimization of costs and maximization of revenues, or that of Kallrath (2002) in which the maximization of the level of sales is set as a purpose, other than previous purposes. Occasionally, some works opt for complementing improvements of an economic nature with improved customer services. Therefore, seven of the references studied set customer-related aspects as their purpose. Specifically, five (Chen et al., 2003; Chen and Lee, 2004; Aliev et al., 2007; Selim et al., 2008; Torabi and Hassini, 2008) establish maximization of the level of service as their objective function, while one reference (Liang and Cheng, 2008) sets minimization of backorders as the purpose of its model. Finally Sabri and Beamon (2000) establish maximization of flexibility as the complementary objective to minimization of costs. Finally, two references (Chen et al., 2003; Chen and Lee, 2004) pursue the maximization of the objectives at the safety inventory levels simultaneously with maximization of revenues and the level of customer services. Romo et al. (2009) consider the maximization of gas flow in each node of the network distribution.

3.5. Shared information

The shared information process is vital for effective supply chain production and transport planning. In terms of centralized planning, this information flows from each node of the network to the node of the chain which will make decisions and will plan the chain. According to Huang et al. (2003), shared information may be classified into six different categories: product, process, recourses, inventory, orders and planning. Table 6 provides the various types of shared information found in the works reviewed.

Tables 7a, 7b and 7c summarizes the various kinds of shared information found in the works reviewed. It is worth highlighting the shared information in relation to production costs and transport. Only five references (Kanyalkar and Adil, 2005; Rizk et al., 2006; Liang and Cheng, 2008; Rizk et al., 2008; Romo et al., 2009) do not consider production costs, like transport costs, which are not considered in Martin et al. (1993), Meijboom and Obel (2007), Liang and Cheng (2008), and in Romo et al. (2009). Other information related to the process, such as lead time, transport time or set-up time, emerges as shared parameters to a lesser extent. As for shared information in terms of inventories, inventory costs stand out as only six works do not consider them. As regards shared information in terms of resource availability, production capacity stands out and, to a lesser extent, information about holding capacity, replenishment or transport. Likewise, only three references feature shared information related to orders (Sabri and

Table 9
Limitations of the reviewed works.

Author	Supply chain structure			Data					Demand
	SNC	DNC	RNC	STNC	LTNC	PCI	TCI	HCI	BDNA
Benjamin (1989)									
Martin et al. (1993)	X		X	X	X				
Chen and Wang (1997)		X		X			X	X	X
Mcdonald and Karimi (1997)	X	X							
Barbarosoğlu and Ozgur (1999)	X			X	X			X	X
Dogan and Goetschalckx (1999)									
Lee and Kim (2000)									X
Sabri and Beamon (2000)			X						
Timpe and Kallrath (2000)	X	X							
Dhaenens-flipo and Finke (2001)	X								
Jayaraman and Pirkul (2001)									
Sakawa et al. (2001)		X							
Bredstrom and Ronnqvist (2002)									
Goetschalckx et al. (2002)									
Jang et al. (2002)									
Kallrath (2002)	X	X							
Lee et al. (2002)	X							X	X
Lee and Kim (2002)	X							X	X
Chen et al. (2003)	X								
Gupta and Maranas (2003)	X						X		
Perea-lopez et al. (2003)				X				X	X
Chen and Lee (2004)	X								
Lababidi et al. (2004)									
Ryu et al. (2004)	X								
Gen and Syarif (2005)	X	X							
Kanyalkar and Adil (2005)	X	X		X	X		X		X
Park (2005)		X						X	X
Demirli and Yimer (2006)				X	X				
Ekşioğlu et al. (2006)	X	X				X	X		X
Lim et al. (2006)				X					
Oh and Karimi (2006)									
Rizk et al. (2006)						X			
Aliev et al. (2007)	X								
Bilgen and Ozkarahan (2007)	X						X		
Chern and Hsieh (2007)	X								
Ekşioğlu et al. (2007)	X	X							X
Meijboom and Obel (2007)		X							
Roghanian et al. (2007)	X								
Jung et al. (2008)	X								
Liang and Cheng (2008)									
Rizk et al. (2008)									
Selim et al. (2008)	X								
Torabi and Hassini (2008)			X						
Romo et al. (2009)	X		X						X

Table 10
Novelty of the reviewed works.

Authors	Novelty
Benjamin (1989)	Simultaneous optimization of production, transport and inventories
Martin et al. (1993)	Integrated planning system which focuses on tactical and operational levels and which also contemplates strategical aspects
Chen and Wang (1997)	Model based on firms and their productive practices
Mcdonald and Karimi (1997)	This work defers demand with penalizations and considers product families. Production is performed in terms of the production centers selected by clients for their replenishment
Barbarosoğlu and Ozgur (1999)	Possession of customers' inventories is penalized in line with the Just In Time production philosophy. Application of Lagrangian relaxation techniques giving way to two models between which information is shared by suboptimizing the gradient. A heuristic algorithm based on the classical minimum spanning tree algorithm is proposed to solve the transport model
Dogan and Goetschalckx (1999)	Supply chain modeling as a flow network which considers the various productive process stages and the different machines inside the production centers
Lee and Kim (2000)	The stochastic character of the production and distribution capacities is considered with simulations. This enables the system's dynamic characteristics to be contemplated: breakdowns, repairs, delays, etc.
Sabri and Beamon (2000)	An integrated model which improves the strategical and operational aspects. Production and distribution demand uncertainty is introduced into the operative submodel. Flexibility in volume and flexible delivery are its purposes, and the variable times to serve orders are considered
Timpe and Kallrath (2000)	Model formulation with different planning horizon time scales in terms of production and sale functions. Commercial aspects are considered, i.e., sales categories according to prices. The possibility of various production modes associated with specific end-product types is contemplated
Dhaenens-flipo and Finke (2001)	Supply chain modeling as a flow network which considers different types of production lines within factories characterized by lengthy set-up times involved in changing the product type to be manufactured
Jayaraman and Pirkul (2001)	It considers strategical aspects for global decision making. This model considers multiple commodities, multiple suppliers of raw materials, multiple factories, warehouses and customers with a heuristics-based solution procedure. This study into model solutions offers information about all the parameters used for this purpose
Sakawa et al. (2001)	An allocation of costs and profits based on the games theory is presented as a complement to the optimum values for production and transport planning
Bredstrom and Ronnqvist (2002)	This work considers production campaigns with a variety of commodities, along with formulas for production using raw materials
Goetschalckx et al. (2002)	A multi-period model for the optimum design of logistics systems, and also for production and distribution planning, which contemplates the production lines in the production centers. A bilinear model is added to establish markup prices
Jang et al. (2002)	This work proposes a model for supply chain integral management policies which includes mathematical modeling to design and plan production and transport in supply chains. Both the models considered break down into three submodels corresponding to the replenishment, production and distribution areas based on the relationships among the various nodes from a list of materials
Kallrath (2002)	A long-term planning horizon with combined strategical and operational planning. Nonlinear modeling characteristics of raw material replenishment costs are considered
Lee and Kim (2002)	The stochastic character of production and distribution capacities are contemplated using simulations that enable the system's dynamic characteristics to be considered: breakdowns, repairs, delays, etc. Simulations with and without randomness are done to generate breakdowns and delays in the supply chain
Lee et al. (2002)	The stochastic character of production and distribution capacities is contemplated using simulations that enable the system's dynamic characteristics to be considered: breakdowns, repairs, delays, etc.
Chen et al. (2003)	A multi-product, multi-period model for planning multiple objectives such as maximizing the level of service, the benefits for each participant and safety inventories, which is solved by applying a two-phase fuzzy method until a compromise solution has been reached
Gupta and Maranas (2003)	Incorporation of demand uncertainty in accordance with probability distribution to create a two-phase stochastic model: one phase contemplates production aspects while the other considers logistic-related aspects, both of which are directly affected by possible variations in demand. This work also contemplates the limitations in production capacities, the inventory transfer between time periods and delayed deliveries
Perea-lopez et al. (2003)	A model predictive control (MPC) application using a moving horizon to optimize profits and to cut down on times in decision making. This work also considers the information shared among the supply chain nodes and delayed deliveries
Chen and Lee (2004)	This includes a robust solution measure in the objective function which avoids variability in the remaining objects in terms of uncertainty. It also considers the demand uncertainty of products and their prices by modeling by stages with associated probabilities and fuzzy sets, respectively
Lababidi et al. (2004)	This includes uncertainty by introducing deviations into the deterministic model. It has three stages whose characteristics differ from the stochastic model. It considers sequencing in the production centers, reactors in this case, to elaborate a production plan which takes into account the constraints and relationships among the various product types
Ryu et al. (2004)	It incorporates production and hold capacities into demand uncertainty models by reformulating them with multi-parametric linear programming
Gen and Syarif (2005)	A hybrid solution method is applied to genetic algorithms based on the so-called spanning tree technique and is complemented with the use of a fuzzy logic controller (FLC)
Kanyalkar and Adil (2005)	An integrated multi-site, multi-product model for multiple points of sales which simultaneously offers tactical and operational level planning in a single phase with planning periods of varying lengths for each decision level. This model does not need detailed information for the whole planning horizon
Park (2005)	A two-phase heuristic model: the first is for the provisional planning of production and distribution, which improves in phase two by the delivery of small orders in full loads in the first planning horizon periods. Comparisons are made with the added advantage of jointly planning production and transport in relation to the sequential planning of both
Demirli and Yimer (2006)	An integrated model for planning built-to-order supply chain production and transport which includes uncertainty in the costs
Ekşioğlu et al. (2006)	The model formulates by applying a heuristics-based primal–dual algorithm to solve a flow problem which helps obtain solutions close to the optimum solution with minor computational effort
Lim et al. (2006)	This work considers the various replenishment forms of raw materials, components and end-products in each node as well as the relationships among these nodes reflected in the corresponding list of materials
Oh and Karimi (2006)	This multi-product model includes regulations in multinational firms, such as company taxes and imports, and tax advantages associated with the refunds of such taxes
Rizk et al. (2006)	This work represents transport costs and scale economies by piecewise linear functions (λ'-*formulation*), and compares two other classical formulations in the literature (λ-formulation and δ-*formulation*)
Aliev et al. (2007)	A fuzzy-genetic approach to aggregate production and transport based on fuzzy mathematical programming which includes uncertainty demand and production capacities. This model is solved by a genetic algorithm

Table 10 (*continued*)

Authors	Novelty
Bilgen and Ozkarahan (2007)	A multi-period optimization model for bulk grain blending and shipping for a supply chain in the cereal sector
Chern and Hsieh (2007)	A heuristic algorithm for master planning that satisfies multiple objectives
Ekşioğlu et al. (2007)	A Lagrangean heuristic technique for production and transport problems. It applies Lagrangean relaxation and decomposition techniques to solve the multi-product flow problem
Meijboom and Obel (2007)	This model studies the operation of a multinational firm which uses two different coordination mechanisms with two different organizational structures. It offers the possibility of customizing the product in terms of the country that sells it
Roghanian et al. (2007)	A probabilistic bi-level linear multi-objective programming model for supply chains using randomness in demand with production capacities and available resources. It uses fuzzy programming to solve the equivalent deterministic multi-objective nonlinear programming model in order to discover a compromise solution
Jung et al. (2008)	This work compares a centralized planning model with a decentralized negotiation model
Liang and Cheng (2008)	Application of fuzzy sets by considering the economic value of time for each category of costs
Rizk et al. (2008)	This is a study into the synchronization of the products flow among the production and distribution centers which use different modes of transport and different delivery times and modeled costs. This study uses piecewise linear functions. It proposes a sequential solution for production and transport subproblems
Selim et al. (2008)	Multi-objective mathematic model for decentralized and centralized collaborative production and transport planning in supply chains. Fuzzy programming has been used to incorporate uncertainty
Torabi and Hassini (2008)	A possibilistic mixed multi-objective linear integer programming model that integrates replenishment, production and distribution planning and considers several conflicting objectives simultaneously, as well as the inaccuracy of certain parameters, such as demand, costs, times and capacities. It uses a fuzzy approach to obtain a compromise solution
Romo et al. (2009)	A decision support tool is developed to optimize the network configuration and routing for the main Norwegian shipper of natural gas, and an independent network operator. This tool is used to evaluate the current network and possible network extensions

Beamon, 2000; Demirli and Yimer, 2006; Chern and Hsieh, 2007) as opposed to information in terms of planning where the level of demand is shared among the various nodes of the supply chains considered in all the references, except Benjamin (1989), Dhaenens-flipo and Finke (2001) and Liang and Cheng (2008).

3.6. Limitations

Some limitations of the supply chain refer to specific nodes (retailers, transport companies, etc.) and their lack of proposed models, or the productive outline of the supply chain which limits its operation. On the other hand, limitations emerge from certain data not being contemplated in the models proposed (pending orders, safety stocks, etc.), or ideal values are determined (not altogether realistic) to determine certain parameters, for example, infinite production capacity.

Table 8 presents the different limitations considered in terms of the supply chain structure, the data processed and demand.

Table 9 summarizes the main limitations identified in all the works reviewed.

3.7. Novelty

Table 10 describes the main novelty contributed by all the works reviewed.

3.8. Application

Table 11 describes the practical application, case studies or the numerical examples to validate the purposes of the works reviewed. Of the 43 works analyzed, 17 were validated through their practical application in case studies.

4. Conclusions

This work presents a review of mathematical programming models for production and transport planning. To study the analyzed works, a classification based on the analysis of eight aspects has been proposed: supply chain structure, decision level, supply chain modeling approach, purpose, shared information, model limitations, the novelty contributed and the practical application. The conclusions drawn from this work affirm that: (1) most of the models reviewed consider a supply chain topology network for production and transport planning oriented to the tactical decision level; (2) the most widely used modeling approach is mixed integer linear programming, where the use of heuristic algorithms and metaheuristics to solve the approach stands out; (3) the purpose of the vast majority of the models proposed is the minimization of the total supply chain costs and, to a lesser extent, the maximization of revenues; (4) the level of demand, production costs, transport and inventory, and production capacity stand out in terms of shared information; (5) the majority of the works reviewed do not contemplate integrated suppliers within the supply chain as most consider the supply chain structure made up of production and distribution centers. In this way, they generally consider replenishment costs or capacities of raw materials, but do not take into account those aspects related to production capacity, forecasting or the suppliers' production plans; and (6) more proposed models validated by numerical examples are presented than case studies applied to real supply chains.

After this review, we pointed out gaps in the literature with proposed future lines of research: (1) it is important to highlight that we have not identified any proposal that can simultaneously optimize transport and production planning beyond considering the costs and capacities associated with a limited transport resource without modeling its own characteristics. Therefore, there is a need for optimization models and tools for the supply chain production and transport planning processes which contemplates transport modeling characteristics (types of collections, associated restrictions, for instance, environmental restrictions, etc.); (2) integration and/or the hierarchical structure of the tactical and operative planning levels in the supply chain context; (3) integration of the suppliers' nodes into the supply chain's optimization models; (4) consideration of the different forms of transport (full truck load, grouping, milk round, routes) products among the various nodes of the supply chain; (5) proposal of a collaborative planning structure which manages the information shared among the supply chain nodes; (6) comparisons made among the centralized and decentralized planning stages of the supply chain; (7) applying the planning models to real case studies; and (8) studying the integration of the optimization, simulation, fuzzy optimization, multi-agent system and evolutive algorithm tools which may support the lines of research considered.

Table 11
Application of the reviewed works.

Authors	Practical applications/numerical examples
Benjamin (1989)	A numerical example comprising 3 supply points and 4 demand points with varying costs, demands and associated capacities
Martin et al. (1993)	A practical application with the supply chain of a glass producer which includes 4 production centers and 40 demand centers for 200 different products
Chen and Wang (1997)	A practical application with a Canadian steel producer that has 5 suppliers of raw materials and 2 semi-manufactured goods, 3 production centers and 3 customer areas
Mcdonald and Karimi (1997)	Two practical applications in the chemicals sector. The first corresponds to 2 production centers which manufacture 34 products including 11 product families over 12 monthly periods. The second corresponds to a single production center with 7 work centers which work in a parallel fashion over two fortnightly periods and two monthly periods to manufacture 14 products
Barbarosoğlu and Ozgur (1999)	120 numerical examples which vary in terms of the number of retailers (2–10), the number of products (2–5), the number of distribution centers (2–10), the planning horizon in months (4–12), and also in terms of demand, capacity and cost characteristics, among others
Dogan and Goetschalckx (1999)	This applies to a study on packing industries with 12 different products and 6 production centers which vary in terms of the number of production lines (81–87), the number of customers (238–714) and in terms of the planning period
Lee and Kim (2000)	A numerical example with 2 mass production centers, 1 warehouse for finished products, 2 intermediary warehouses and 3 retailers
Sabri and Beamon (2000)	A numerical example with 3 kinds of raw materials, 2 end-products, 3 production centers and 4 distribution centers at 5 different stages
Timpe and Kallrath (2000)	A case study of the chemical industry with 4 manufacturing plants, 5 modes of production, 1 type of raw material used and 4 points of sales for 12 business periods and 36 production periods
Dhaenens-flipo and Finke (2001)	A practical application with an engineering company that has 10 production centers, 16 production lines, 16 different products, 50 warehouses and 300 retail points
Jayaraman and Pirkul (2001)	Numerical examples in terms of varying numbers of suppliers (1–2), the number of raw materials used (2–3), production centers (3–10), warehouses (3–15), and retailers (5–75)
Sakawa et al. (2001)	Case study of a Japanese firm that manufactures construction elements and has 5 production centers
Bredstrom and Ronnqvist (2002)	Case study of the supply chain of a Swedish paper mill firm, a world leader in its sector
Goetschalckx et al. (2002)	Case study about the packing industry with 12 different products, 6 production centers with a varying number of production lines (81–87), number of customers (238–714) and planning period
Jang et al. (2002)	10 numerical examples in which the number of suppliers (1–6), the number of production centers (1–4), distribution centers (1–3) and retailers (1–4) varies, and which include 5 periods, end-products (3–4) and components (3–4)
Kallrath (2002)	A case study applied to the chemical industry
Lee and Kim (2002), Lee et al. (2002)	A numerical example with 2 mass production centers, 1 warehouse for finished products, 2 intermediary warehouses and 3 retailers
Chen et al. (2003)	A numerical example with a production plant, 2 warehouses or distribution centers, 2 retailers and 2 products
Gupta and Maranas (2003)	A numerical example with 6 production centers, 30 different products grouped into 10 product families whose demand is distributed normally
Perea-lopez et al. (2003)	A numerical example with 3 production centers, 4 warehouses, 10 retailers, 20 customers and 9 different products
Chen and Lee (2004)	A numerical example made up of 1 manufacturing center, 2 distribution centers, 2 retailers and 2 products. One distribution center acts rapidly and delivers small lot sizes, while the other serves large-sized lots with scale economies
Lababidi et al. (2004)	A case study corresponding to a petrochemical industry for a 6-month planning horizon, with 2 reactors, 15 products distributed in 2 product families, and 11 customers
Ryu et al. (2004)	A numerical example made up of 3 production centers, 2 distribution centers, 2 retailers or markets and 2 products
Gen and Syarif (2005)	Three numerical examples in which the number of periods (2–4–6), the number of products (3–3–2), the number of manufacturing centers (3–4–7), production resources (2–3–4), and the number of retailers (7–10–21) vary
Kanyalkar and Adil (2005)	A consumer goods industry with 9 products, 5 manufacturing centers and 19 points of sale
Park (2005)	Three numerical examples in terms of the number of factories (2–5), retailers (5–70), products (2–5) and periods (5–12)
Demirli and Yimer (2006)	A numerical example with 3 suppliers, 1 manufacturing center, 2 distribution centers and 4 retailers
Ekşioğlu et al. (2006)	A numerical example with 3 factories, 1 retailer and 2 periods. Calculations have been done for 15 different network typologies where the number of production centers (20–40) and the number of periods (24–384) vary, with a single retailer. Comparisons between the original mathematical programming problem, and the relaxation and heuristics techniques are presented. Nine additional cases are presented which consider multiple retailers whose parameters differ from the previous ones
Lim et al. (2006)	27 different numerical examples are presented in terms of both the different replenishment practices and the number of suppliers, factories, distribution centers, end customers and products
Oh and Karimi (2006)	A numerical example of a total of 8 suppliers, 12 factories and 10 customers, all spread out in 10 countries, with twice-weekly periods up to one year
Rizk et al. (2006)	A case study of the paper industry. Twelve different cases are studied in which the transport structure (full or part load), the different numbers of intervals in terms of transport costs (8–18 in the first case and 3–7 in the second case), the number of products (two groups of 50–100 and 250–300 products), the number of periods (15–30), and demand variation differ
Aliev et al. (2007)	A numerical example made up of 2 manufacturing centers, 2 distribution centers and 2 retailers with two time periods
Bilgen and Ozkarahan (2007)	A case study with 3 ports, 2 customers, 2 original products and one product mixed with a single bulk carrier type
Chern and Hsieh (2007)	Numerical examples of two kinds of demands characterized by different priorities, delay costs and the same article. Four different stages have been modeled, and delays and the possibility of subcontracting production have been considered using two solution methods with different levels of demanded units
Ekşioğlu et al. (2007)	Small-sized numerical examples with 3 production centers, 6 retailers, 3 products and 7 periods. 20 different problems have been solved by defining demand intervals and set-up costs. A total of 35 more complex problems have also been solved by increasing the number of factories, retailers, products and periods
Meijboom and Obel (2007)	A case study of a leading pharmaceutical firm in the European market. This work considers 3 products, 5 suppliers, 2 production centers, and 3 markets. Two functional typologies have also been compared to assess coordination
Roghanian et al. (2007)	A numerical example made up of 2 manufacturing centers, 1 distribution center, 1 retailer and 2 products
Jung et al. (2008)	A numerical example with 4 product types, 10 manufacturing centers, 5 distribution centers, 10 markets or retailers
Liang and Cheng (2008)	A case study of a world manufacturer of mechanical elements which considers 2 products, 2 production centers and 4 distribution centers
Rizk et al. (2008)	A practical application of an industry in the paper sector. Four different cases have been studied in which the number of modes of transport (1–2), the number of destinations or distribution centers (5–10) vary, while the number of end-products remains the same (100)

Table 11 (*continued*)

Authors	Practical applications/numerical examples
Selim et al. (2008)	A numerical example made up of 3 manufacturing centers, 3 distribution centers, 5 retailers and 3 customers with 5 product types
Torabi and Hassini (2008)	A numerical example made up of 4 suppliers, 1 manufacturing and 3 distribution centers for a 3-month planning horizon with weekly periods
Romo et al. (2009)	A case study corresponding to a Norwegian gas shipper and a network operator

Finally, this issue reflects the gap to be bridged between academic research and commercial applications. In an ideal world, academic research would address real-world modeling needs not captured by commercial systems. For example, the stochastic programming processing of demand and other uncertain factors, or, the integration of vehicle routing with a location analysis of distribution centers.

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References

Aliev, R.A., Fazlollahi, B., Guirimov, B.G., Aliev, R.R., 2007. Fuzzy-genetic approach to aggregate production–distribution planning in supply chain management. Information Sciences 177, 4241–4255.

Barbarosoğlu, G., Ozgur, D., 1999. Hierarchical design of an integrated production and 2-echelon distribution system. European Journal of Operational Research 118, 464–484.

Beamon, B.M., 1998. Supply chain design and analysis: models and methods. International Journal of Production Economics 55, 281–294.

Beamon, B.M., Chen, V.C.P., 2001. Performance analysis of conjoined supply chains. International Journal of Production Research 39, 3195–3218.

Benjamin, J., 1989. An analysis of inventory and transportation cost in a constrained network. Transportation Science 23, 177–183.

Bilgen, B.y., Ozkarahan, I., 2004. Strategic tactical and operational production–distribution models: a review. International Journal of Technology Management 28, 151–171.

Bilgen, B., Ozkarahan, I., 2007. A mixed-integer linear programming model for bulk grain blending and shipping. International Journal of Production Economics 107, 555–571.

Bredstrom, D., Ronnqvist, M., 2002. Integrated production planning and route scheduling in pulp mill industry. In: Proceedings of the 35th Annual Hawaii International Conference on System Sciences, 2002. HICSS.

Chen, C.L., Lee, W.C., 2004. Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices. Computers and Chemical Engineering 28, 1131–1144.

Chen, M., Wang, W., 1997. A linear programming model for integrated steel production and distribution planning. International Journal of Operations and Production Management 17, 592–610.

Chen, C.L., Wang, B.W., Lee, W.C., 2003. Multiobjective optimization for a multienterprise supply chain network. Industrial and Engineering Chemistry Research 42, 1879–1889.

Chern, C.C., Hsieh, J.S., 2007. A heuristic algorithm for master planning that satisfies multiple objectives. Computers and Operations Research 34, 3491–3513.

Demirli, K., Yimer, A.D., 2006. Production–Distribution Planning with Fuzzy Costs, Fuzzy Information Processing Society, 2006. NAFIPS 2006. Annual meeting of the North American, pp. 702–707 (3–6 June).

Dhaenens-flipo, C., Finke, G., 2001. An integrated model for an industrial production–distribution problem. IIE Transactions 33, 705–715.

Dogan, K., Goetschalckx, M., 1999. A primal decomposition method for the integrated design of multi-period production–distribution systems. IIE Transactions 31, 1027–1036.

Dullaert, W., Bräysy, O., Goetschalckx, M., Raa, B., 2007. Supply chain (re)design: support for managerial and policy decisions. European Journal of Transport and Infrastructure Research 7 (2), 73–92.

Ekşioğlu, S.D., Romeijn, H.E., Pardalos, P.M., 2006. Cross-facility management of production and transportation planning problem. Computers and Operations Research 33, 3231–3251.

Ekşioğlu, S.D., Ekşioğlu, B., Romeijn, H.E., 2007. A Lagrangean heuristic for integrated production and transportation planning problems in a dynamic, multi-item, two-layer supply chain. IIE Transactions 39, 191–201.

Erenguc, S.S., Simpson, N.C., Vakharia, A.J., 1999. Integrated production/distribution planning in supply chains: an invited review. European Journal of Operational Research 115, 219–236.

Gen, M.S., Syarif, A., 2005. Hybrid genetic algorithm for multi-time period production/distribution planning. Computers and Industrial Engineering 48, 799–809.

Goetschalckx, M., Vidal, C.J., Dogan, K., 2002. Modeling and design of global logistics systems: a review of integrated strategic and tactical models and design algorithms. European Journal of Operational Research 143, 1–18.

Gupta, A., Maranas, C.D., 2003. Managing demand uncertainty in supply chain planning. Computers and Chemical Engineering 27, 1219–1227.

Huang, G.Q., Lau, J.S.K., Mak, K.L., 2003. The impacts of sharing production information on supply chain dynamics: a review of the literature. International Journal of Production Research 41, 1483–1517.

Jang, Y.J., Jang, S.Y., Chang, B.M., Park, J., 2002. A combined model of network design and production/distribution planning for a supply network. Computers and Industrial Engineering 43, 263–281.

Jayaraman, V., Pirkul, H., 2001. Planning and coordination of production and distribution facilities for multiple commodities. European Journal of Operational Research 133, 394–408.

Jung, H., Jeong, B., Lee, C.G., 2008. An order quantity negotiation model for distributor-driven supply chains. International Journal of Production Economics 111, 147–158.

Kallrath, J., 2002. Combined strategic and operational planning – an MILP success story in chemical industry. Or Spectrum 24, 315–341.

Kanyalkar, A.P., Adil, G.K., 2005. An integrated aggregate and detailed planning in a multi-site production environment using linear programming. International Journal of Production Research 43, 4431–4454.

Lababidi, H.M.S., Ahmed, M.A., Alatiqi, I.M., Al-enzi, A.F., 2004. Optimizing the supply chain of a petrochemical company under uncertain operating and economic conditions. Industrial and Engineering Chemistry Research 43, 63–73.

Lee, Y.H., Kim, S.H., 2000. Optimal production–distribution planning in supply chain management using a hybrid simulation-analytic approach. Proceedings of the 2000 Winter Simulation Conference 1 and 2, 1252–1259.

Lee, Y.H., Kim, S.H., 2002. Production–distribution planning in supply chain considering capacity constraints. Computers and Industrial Engineering 43, 169–190.

Lee, Y.H., Kim, S.H., Moon, C., 2002. Production–distribution planning in supply chain using a hybrid approach. Production Planning and Control 13, 35–46.

Liang, T.-F., Cheng, H.-W., 2008. Application of fuzzy sets to manufacturing/distribution planning decisions with multi-product and multi-time period in supply chains. Expert Systems with Applications 36, 3367–3377.

Lim, S.J., Jeong, S.J., Kim, K.S., Park, M.W., 2006. A simulation approach for production–distribution planning with consideration given to replenishment policies. International Journal of Advanced Manufacturing Technology 27, 593–603.

Martin, C.H., Dent, D.C., Eckhart, J.C., 1993. Integrated production, distribution, and inventory planning at Libbey–Owens–Ford. Interfaces 23, 78–86.

Mcdonald, C.M., Karimi, I.A., 1997. Planning and scheduling of parallel semicontinuous processes. 1. Production planning. Industrial and Engineering Chemistry Research 36, 2691–2700.

Meijboom, B., Obel, B., 2007. Tactical coordination in a multi-location and multi-stage operations structure: a model and a pharmaceutical company case. Omega-International Journal of Management Science 35, 258–273.

Oh, H.C., Karimi, I.A., 2006. Global multiproduct production–distribution planning with duty drawbacks. AICHE Journal 52, 595–610.

Park, Y.B., 2005. An integrated approach for production and distribution planning in supply chain management. International Journal of Production Research 43, 1205–1224.

Perea-lopez, E., Ydstie, B.E., Grossmann, I.E., 2003. A model predictive control strategy for supply chain optimization. Computers and Chemical Engineering 27, 1201–1218.

Rizk, N., Martel, A., D'amours, S., 2006. Multi-item dynamic production–distribution planning in process industries with divergent finishing stages. Computers and Operations Research 33, 3600–3623.

Rizk, N., Martel, A., D'amours, S., 2008. Synchronized production-|distribution planning in a single-plant multi-destination network. Journal of the Operational Research Society 59, 90–104.
Roghanian, E., Sadjadi, S.J., Aryanezhad, M.B., 2007. A probabilistic bi-level linear multi-objective programming problem to supply chain planning. Applied Mathematics and Computation 188, 786–800.
Romo, F., Tomasgard, A., Hellemo, L., Fodstad, M., Eidesen, B.H., Pedersen, B., 2009. Optimizing the Norwegian Natural gas production and transport. Interfaces 39 (1), 46–56.
Ryu, J.H., Dua, V., Pistikopoulos, E.N., 2004. A bilevel programming framework for enterprise-wide process networks under uncertainty. Computers and Chemical Engineering 28, 1121–1129.
Sabri, E.H., Beamon, B.M., 2000. A multi-objective approach to simultaneous strategic and operational planning in supply chain design. Omega-International Journal of Management Science 28, 581–598.
Sakawa, M., Nishizaki, I., Uemura, Y., 2001. Fuzzy programming and profit and cost allocation for a production and transportation problem. European Journal of Operational Research 131, 1–15.
Schmidt, G., Wilhelm, W.E., 2000. Strategic, tactical and operational decisions in multi-national logistics networks: a review and discussion of modelling issues. International Journal of Production Research 38, 1501–1523.
Selim, H., Am, C., Ozkarahan, I., 2008. Collaborative production–distribution planning in supply chain: a fuzzy goal programming approach. Transportation Research Part E-Logistics and Transportation Review 44, 396–419.
Shah, N., 2005. Process industry supply chains: advances and challenges. Computers and Chemical Engineering 29, 1225–1235.
Stadtler, H., 2005. Supply chain management and advanced planning – basics, overview and challenges. European Journal of Operational Research 163, 575–588.
Timpe, C.H., Kallrath, J., 2000. Optimal planning in large multi-site production networks. European Journal of Operational Research 126, 422–435.
Torabi, S.A., Hassini, E., 2008. An interactive possibilistic programming approach for multiple objective supply chain master planning. Fuzzy Sets and Systems 159, 193–214.
Vidal, C.J., Goetschalckx, M., 1997. Strategic production–distribution models: a critical review with emphasis on global supply chain models. European Journal of Operational Research 98, 1–18.