A typology and literature review on stochastic multi-echelon inventory models

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Abstract

We develop a typology for multi-echelon inventory management. The typology is used to classify and review the extensive research of multi-echelon inventory management under uncertain demand. We identify clusters of model assumptions, research goals and applied methodologies. Based on this review, existing research gaps and avenues for further research are proposed.

Keywords: Supply chain management, inventory, multi-echelon, demand uncertainty, typology

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1 Introduction

Multi-echelon inventory management and theory have a research and publication history of more than 50 years. Ground-breaking seminal papers in the late 1950s/early 1960s stimulated a huge amount of theoretical and applied research, which resulted in trees of new and refined research directions. With the increasing popularity of supply chain management in the literature as well as in industrial practice, its core building block – multi-echelon inventory models – gained further attention and importance.

The earlier work under stochastic demand predominantly focused on exact models and on deriving structural properties of optimal inventory policies under very stylized assumptions. As determining optimal policy structures turned out to be intractable even for basic multi-echelon structures, such as pure divergent structures, due to complex non-linearity of cost functions and the well-known curses of dimensionality in dynamic programming, follow-up research during the 1980s and 1990s investigated the optimal or heuristic setting of parameters for given policy structures, e.g., base stock policies. Around the year 2000, this research resulted in various approaches to optimize policies for general structures, i.e., where items in the supply chain can have multiple successors and multiple predecessors. In doing so, the field enabled the "optimization" of real-world supply chains, which was recognized by multinational companies. It also led to the development of commercial multi-echelon inventory optimization software. The pioneering companies became known as SmartOps (acquired by SAP), Optiant (acquired by Logility), and LogicTools (acquired by IBM). The fact that operations research faculty start-ups were bought out shows both the interest in the field of multi-echelon inventory optimization, its high practical relevance and the complexity of the problem to be solved.

The next wave of multi-echelon inventory research under uncertain demand concerned the integration of different flexibility options. This type of research is rooted in the spare parts inventory management arena, as spare parts inventory systems are characterized by high capital investments, low demand rates, and high service requirements. Exploiting flexibility options such as expediting, transshipments and other forms of inventory pooling, as well as outsourcing of repairs, has a big impact on the capital investments needed to meet the customer service requirements. This research on spare parts systems was further stimulated by changes in business models of OEMs under the heading "power by the hour": OEMs do not deliver spare parts to their customers, but ensure uptime of the customers' equipment.

Another shift is a transition from mathematically elegant models to policies and algorithms for today's inventory decision support tools that can be implemented in practice, along with a shift from analytical to approximate/numerical studies due to enlarged computational capabilities. Interestingly, our assessment of the state-of-the-art on multi-echelon inventory systems under uncertain demand shows that, over the last decade, there has been a renewed interest in the structure of optimal policies, albeit for small-scale systems with a specific structure and specific assumptions on demand and replenishment processes.

1.1 Motivation and objectives

Over the years, several review papers have structured the field of multi-echelon inventory models (see Section 1.2). What is still missing is a structured classification of model assumptions that enables a fast and well-accepted terminology for core assumptions of a model and its underlying system. Such classification schemes are common in other areas of operations management and operations research, see Kendall (1953) and Buzacott and Shanthikumar (1993) for queuing models, Dyckhoff (1990) and Wäscher et al. (2007) for cutting and packing, Graham et al. (1979) for scheduling models, Brucker et al. (1999) for project planning, Boysen et al. (2007) for assembly line balancing, and Copil et al. (2017) for lot-sizing and scheduling.

We provide such a classification scheme for multi-echelon inventory models and showcase it in an up-to-date literature review on models under demand uncertainty for the reason of keeping focus, and realizing, to a certain degree, similar kinds of assumptions and methodologies, compared to literature streams on lot-sizing and scheduling, which primarily focussed on deterministic demands. In more recent articles, we see the assessment of deterministic models regarding their effectiveness under stochastic demand (e.g., de Kok and Fransoo (2003), Jansen et al. (2013)) and the inclusion of uncertain demand into lot-sizing and scheduling problems.

The contributions of this paper are the following:

- We propose a typology for multi-echelon inventory systems.
- We provide an extensive literature review of 394 papers under demand uncertainty until end of 2016, classified according to our typology.
- We identify seminal papers that started research streams and have been most-cited.
- We identify research gaps.

Moreover, we present a documentation of our classification process that shows how the classification can be kept up-to-date in the future. The objectives of developing a typology in the first place are:

1. We want to explicitly state all important dimensions of modeling assumptions (e.g., the structure of the system, the demand processes, the replenishment processes, the objectives, ...) so that methods can be compared appropriately.
2. We want to assess how modeling assumptions disseminate over time so that pivotal papers and the emergence of separate research branches become visible.

3. We want to guide practitioners towards characterizing their real-world supply chain structures so that it becomes easy to link the supply chain problems they encounter in practice to the existing literature.

We documented our classification in the form of a bibtex database. This database allows us to generate further insights into the state-of-the-art through exploratory data analysis. We present our findings in the form of qualitative statements. Our data analysis, finally, leads to the above-mentioned identification of research gaps, i.e., practically and scientifically relevant models of multi-echelon inventory systems that need further study.

As an additional service to the research community, we make publically available a continuously updated bibtex database of multi-echelon inventory literature that contains our classification data at

http://www.modus.uni-bayreuth.de/en/Projects/projects_academia/MEIO/index.html.

1.2 Methodology

In the following, we describe our literature search and classification strategy (Denyer and Trenfield 2009). The initial search was based on a literature list compiled from earlier review articles on multi-echelon inventory systems under uncertain demand. First, the handbooks on operations research and management science, in particular the chapters by Axsäter (1993a), Federgruen (1993), Graves and Willems (2003), Axsäter (2003c), Song and Zipkin (2003), and de Kok and Fransoo (2003) were used. Second, reviews from the European Journal of Operational Research were included: van Houtum, Inderfurth, et al. (1996) and Diks, de Kok, and Lagodimos (1996). More recent reviews are Gümüs and Güneri (2007), Simchi-Levi and Zhao (2011) and Eruguz, Sahin, et al. (2016). This list was then supplemented by a backward search using Google Scholar. To remain as focused as possible, we excluded all manuscripts that assume deterministic demand, single periods or single stages. For each of the remaining papers, two members of the team of authors were randomly assigned to classify them using the typology introduced in Section 2. In several consensus meetings with all the authors, conflicting classifications were resolved to obtain the final classification. Publications classified as being out of scope were removed from the list. In this way, we considered all papers with a publication date up to the end of 2016.

1.3 Structure of the paper

The paper is organized as follows. In Section 2, we present the typology of (stochastic) multi-echelon inventory systems, i.e., the structural elements that constitute these systems. In Sections 3 and 4, we use our typology to classify and discuss the current state of the art concerning stochastic multi-echelon inventory systems and to identify research gaps and topics for further research. In Section 5, we reflect on our findings and summarize the main conclusions.

2 Typology

In Table 1, we present the typology. The first column names the dimension of the typology, the second column the possible values, the third column is the explanation, and the fourth column shows the number of papers for which the classification includes this value for papers under stochastic demand. Note that counts for single-echelon and deterministic models are not available (n.a.) as these are out of scope for our literature review. As papers can have multiple values within one dimension of the typology, the sum of these numbers can exceed the total number of classified papers. We further introduce the following typology string:

<No. of Echelons>, <Structure>, <Time>, <Information> | <Capacity>, <Delay> |
<Demand>, <Customer> | <Policy>, <Lotsize>, <Flexibility> | <Performance Indicator> ||
<Methodology>, <Research Goal>

This string is divided into two main parts. The first part concerns the problem under investigation and is divided into five sections. The first section is the system specification and contains information about the supply chain as a network hosting a dynamic process. The second section specifies how resources can be used for the materials flow. Interaction with the external market is represented in the third section. The fourth section deals with the business rules that may restrict the types of policies that can be used. Finally, the last section characterizes what "good performance of a policy in the system" is supposed to mean. This last dimension has to be distinguished from the performance assessment of an optimization algorithm used to compute a policy, like CPU time or approximation quality. The second part contains information about the methodology of the paper, i.e., how the results have been derived, and the research goal, i.e., what type of result has been presented.

Typology			
Dimension	*Values*	*Explanation*	*Number of papers*
The problem under investigation:			
System Specification:			
Echelons	Number of echelons		

Typology			
Dimension	*Values*	*Explanation*	*Number of papers*
	1	single echelon	n.a.
	2	two echelons	244
	3	three echelons	6
	4	four echelons	1
	n	general number of echelons	146
	x	continuous	1
Structure	Relationship between items		
	C	convergent material structure: one successor, multiple predecessors	42
	D	divergent material structure: multiple successors, one predecessor	189
	G	general material structure: multiple successors, multiple predecessors	88
	S	serial material structure: one successor, one predecessor	91
Time	Moments in time where relevant events occur		
	C	continuous: actions possible at any point in time	198
	D	discrete: actions possible at specific points in time	197
Information	Level of information needed to perform the computations		
	E	echelon: everything downstream	5
	G	global: everything	380
	L	local: single node only	12
Resources Specification:			
Capacity	Restriction on availability of resources		
	F	bounded storage and/or processing capacity	71
	I	infinite capacity (no constraint)	325
Delay	Time it takes to deliver an item (including production times, excluding stock-out delays)		
	C	constant	299
	E	exponential	38
	G	general stochastic	62
	O	other: for a restricted set of distributions, different from C, E, G	2
Market Specification:			
Demand	Exogenous demand for an item		

Typology			
Dimension	*Values*	*Explanation*	*Number of papers*
	C	deterministic	n.a.
	B	compound "batch" Poisson	40
	D	discrete stochastic	15
	G	general stochastic	138
	M	Markovian, i.e., state-dependent Poisson	6
	N	Normal	50
	P	Poisson	127
	R	compound renewal	9
	U	upper-bounded: typically used in guaranteed service models	44
Customer	Attributes (reactions to disservice, advanced demand, etc.)		
	B	backordering	321
	G	guaranteed service	42
	L	lost sales	43
Control Type Specification:			
Policy	Prescribed type of replenishment policy		
	N	none	61
	B	echelon base stock	42
	b	installation base stock	163
	S	echelon (s, S)	2
	s	installation (s, S)	10
	Q	echelon (s, nQ)	17
	q	installation (s, nQ)	67
	O	other	49
Lot-sizing	Constraint on release quantity		
	F	flexible: no restriction	310
	Q	fixed order quantity: order quantity is restricted, but multiple orders of prescribed size at the same moment are allowed	85
	O	other	3
Operational flexibility	Capability to use other means of satisfying unexpected requirements than originally foreseen		
	N	none	267
	A	allocation	29
	E	expediting	24
	O	outsourcing	12
	R	routing flexibility: item from another source to customer, another item to customer	36
	U	unspecified	37

Typology			
Dimension	*Values*	*Explanation*	*Number of papers*
Performance Specification:			
Performance indicator	Objective to be achieved as a result of selection of control policy and its parameters		
	E	equilibrium	6
	S	meeting operational service requirements	75
	C	minimization of costs	335
	M	multi-objective (efficient frontier)	15
	U	unspecified	8
Generic scientific aspects of the Paper:			
Methodology	Techniques applied to achieve the results		
	A	approximative	221
	C	computational experiments	196
	E	exact	173
	F	field study	17
	S	simulation	48
Research goal	Goal of the investigations		
	C	comparison	46
	F	formulae	14
	O	optimization	277
	P	performance evaluation	75

Table 1: Typology

For completeness, the typology includes single-echelon systems and deterministic demand. Obviously, several other categories are not relevant for such models, e.g. the structure and information for single echelon system or demand distributions and flexibility measure for deterministic demand. The classification with regard to the number of echelons and the distinction of network topologies into the three basic types of serial, convergent (comprises assembly and multi-sourcing, usually the first), divergent (comprises distribution and disassembly, so far only the first) and general is straightforward, as is the separation between continuous and discrete time approaches. In the information category, most publications were classified as requiring global information. Even though demand information was only partially available, the overall optimization of system parameters across stages requires such global information. Capacity issues were divided into infinite and finite, where the latter includes any kind of manufacturing and space limitations. Furthermore, we use the term delay instead of lead time to distinguish between the pure delivery process and delays caused by stockouts, which themselves are a result of the policy applied and can therefore not be regarded as being data of the problem statement.

In categorizing demand, we selected several popular distributions in multi-echelon inventory theory, such as Poisson, compound Poisson or normal, while including general continuous and discrete as being other desirable entries. As the guaranteed service model has received particular attention in the research area but at the same time often includes a specific model of demand being bounded, we added it as an additional entry. In the policy categorization, the main distinction is between installation and echelon stock policies on the one hand and (s, S) and (s, nQ)-type policies on the other hand. The combination of both subproblems spans the entries in this field. For lot-sizing, we allow quantities both to be fixed or flexible, which includes papers investigating optimal policies that require no upfront limitation with regard to quantities.

A particular interest of our later analysis is devoted to the use of flexibility. Although the majority of papers classified follows a linear, unique, and direct flow through the network, multi-echelon systems include a variety of deviations from this assumption to allow for more flexibility. In order to indicate these different types of flexibility options, we included allocation, expediting, outsourcing, and routing flexibility, the last including the famous transshipment option.

In the category of performance measurement, we allow for the widely used metrics of cost minimization and attaining required service levels. For a broader perspective, the category equilibrium allows for multiple decision makers and we might also have multiple objectives.

With regard to methodology, we distinguish between approximative and exact methods. The choice depends on whether an approximation (abstraction from reality through modeling) is made when introducing the system assumptions or later during the analysis. For example, METRIC introduces random demand resulting in random delays which are replaced by their expected value during the analysis. Therefore, the METRIC papers are classified as approximate. However, the guaranteed service model (GSM) makes the assumption that such delays are covered by flexibility measures (or excluded by bounded demand). Therefore, the GSM papers are classified as exact. Furthermore, computational experiments and simulation are distinguished. Only those papers that use simulation to quantify performance measures were classified as such whereas the use of simulation to test the quality of approximations was subsumed under computational experiments. The category describing the research goal allows for optimization approaches. Other ambitions might include the derivation of closed-form formulas or performance evaluation of strategies or their comparison.

Of course, several choices had to be made in the above classification scheme. We use standard terminology where convenient, although other choices might be more appropriate depending on the application context.

Obviously, the full typology string for a problem specification is difficult to decipher. Thus, we present a condensed variant of it. The fine-grained typology above can then be used in a longer introduction to technically put a result into context. In our opinion, the condensed typology string should reflect differences in the problem setting that also have an impact on the methods used to investigate them.

Condensed Typology

Dimension	*Values*	*Explanation*	*Number of papers*
Echelons	Number of echelons		
	1	single echelon	n.a.
	2	two echelons	244
	n	general number of echelons	153
Structure	Relationship between items		
	C	convergent material structure	42
	D	divergent material structure	189
	G	general material structure	88
	S	serial material structure	91
Capacity	Restriction on availability of resources		
	F	finite storage and/or processing capacity	71
	I	infinite capacity (no constraint)	325
Delay	Time it takes to deliver an item (including production times, excluding stock-out delays)		
	C	constant	299
	G	general stochastic	62
	O	other: prescribed distribution	40
Demand	Exogenous demand for an item		
	C	Deterministic	n.a.
	G	general (including discrete) stochastic	153
	N	Normal-type demand	50
	O	other: prescribed distribution	55
	P	Poisson-type demand	127
	U	upper-bounded: typically used in guaranteed service models	44
Customer	Attributes (reactions to disservice, advanced demand, etc.)		
	B	backordering	321
	G	guaranteed service	42
	L	lost sales	43
Restrictions	Prescribed operational restrictions		

Condensed Typology			
Dimension	*Values*	*Explanation*	*Number of papers*
	N	none: arbitrary policy possible	61
	P	policy: prescribed policy class	332
	Q	quantity: prescribed lot-sizing policy	97
Performance indicator	Objective to be achieved as a result of selection of control policy and its parameters		
	C	minimal cost (in the general sense)	335
	S	achieve service-level (in the general sense)	75

Table 2: Condensed typology

For the condensed version, we add the dimensions as superscripts to the values in order to make the typology string decipherable without reference to a table or something similar to it. Thus, a general classification string would look like the following:

$$\texttt{<}k\texttt{>}^{\mathrm{ech}}\texttt{,<top.>}^{\mathrm{net}}|\texttt{<cap.>}^{\mathrm{cap}}\texttt{,<del.>}^{\mathrm{del}}|\texttt{<dem.>}^{\mathrm{dem}}\texttt{,<cust.>}^{\mathrm{cus}}|\texttt{<restr.>}^{\mathrm{res}}|\texttt{<obj.>}^{\mathrm{obj}}$$

For illustration, we report the classification of six seminal papers in the field of multi-echelon inventory control under uncertainty by using our framework. In chronological order, Simpson (1958) and Clark and Scarf (1960) founded the so-called research streams on guaranteed and stochastic service models. Detailed foundations for divergent systems were Sherbrooke (1968) for continuous review low-demand systems and Eppen and Schrage (1981) for periodic review distribution systems. Later, Rosling (1989) treated convergent systems exactly while Lee, So, et al. (2000) is the most cited fundamental contribution on the bullwhip effect.

Our classification shows how each paper initiated a new research stream and added new knowledge to the field of multi-echelon optimization. We point this out by highlighting some key characteristics of each paper. Simpson (1958) introduced a serial system using a continuous time model and a guaranteed service model (structure S, time C, customer G). Insights on serial systems with a discrete time model and a backorder customer type were first published by Clark and Scarf (1960) (structure S, time D, customer B). The restriction to serial systems was overcome by Sherbrooke (1968) (structure D, time C) for continuous time and by Eppen and Schrage (1981) (structure D, time D) for discrete time, who introduced divergent distribution systems. Subsequently, Rosling (1989) used a convergent system (structure C). Lee, So, et al. (2000) showed the bullwhip effect for a serial system with discrete time, and their methodology is exact as well as computational (methodology EC). While the research goal of all other seminal papers mentioned here is optimization, theirs is comparison (goal C).

1. Simpson (1958): Long: `n,S,C,G|I,C|U,G|b,F,U|C||E,O`
   Short: $\mathtt{n}^{\text{ech}}\mathtt{,S}^{\text{net}}\mathtt{|I}^{\text{cap}}\mathtt{,C}^{\text{del}}\mathtt{|U}^{\text{dem}}\mathtt{,G}^{\text{cus}}\mathtt{|P}^{\text{res}}\mathtt{|C}^{\text{obj}}$

2. Clark and Scarf (1960): Long: `n,DS,D,G|I,C|G,B|N,F,N|C||E,O`
   Short: $\mathtt{n}^{\text{ech}}\mathtt{,DS}^{\text{net}}\mathtt{|I}^{\text{cap}}\mathtt{,C}^{\text{del}}\mathtt{|G}^{\text{dem}}\mathtt{,B}^{\text{cus}}\mathtt{|N}^{\text{res}}\mathtt{|C}^{\text{obj}}$

3. Sherbrooke (1968): Long: `2,D,C,G|I,G|B,B|b,F,N|C||A,O`
   Short: $\mathtt{2}^{\text{ech}}\mathtt{,D}^{\text{net}}\mathtt{|I}^{\text{cap}}\mathtt{,G}^{\text{del}}\mathtt{|P}^{\text{dem}}\mathtt{,B}^{\text{cus}}\mathtt{|P}^{\text{res}}\mathtt{|C}^{\text{obj}}$

4. Eppen and Schrage (1981): Long: `2,D,D,G|I,C|N,B|B,F,N|C||E,O`
   Short: $\mathtt{2}^{\text{ech}}\mathtt{,D}^{\text{net}}\mathtt{|I}^{\text{cap}}\mathtt{,C}^{\text{del}}\mathtt{|N}^{\text{dem}}\mathtt{,B}^{\text{cus}}\mathtt{|P}^{\text{res}}\mathtt{|C}^{\text{obj}}$

5. Rosling (1989): Long: `n,C,D,G|I,C|G,B|N,F,N|C||E,O`
   Short: $\mathtt{n}^{\text{ech}}\mathtt{,C}^{\text{net}}\mathtt{|I}^{\text{cap}}\mathtt{,C}^{\text{del}}\mathtt{|G}^{\text{dem}}\mathtt{,B}^{\text{cus}}\mathtt{|N}^{\text{res}}\mathtt{|C}^{\text{obj}}$

6. Lee, So, et al. (2000): Long: `2,S,D,G|I,C|G,B|b,F,O|C||EC,C`
   Short: $\mathtt{2}^{\text{ech}}\mathtt{,S}^{\text{net}}\mathtt{|I}^{\text{cap}}\mathtt{,C}^{\text{del}}\mathtt{|G}^{\text{dem}}\mathtt{,B}^{\text{cus}}\mathtt{|P}^{\text{res}}\mathtt{|C}^{\text{obj}}$

In the next two sections, we discuss the main insights obtained from the classification. We use our typology to categorize these insights. Let us remark here that those insights do not relate to managerial insights obtained in these papers, but to the development of knowledge over a period of about 60 years in terms of the assumptions necessary for rigorous analysis. All graphs present a longitudinal perspective on every one of the classification dimensions. Note that, since papers can serve more than one purpose at the same time, percentages may exceed 100%.

3 Insights on methodology and research goals

In this section, we discuss the generic scientific aspects of the classified papers. This concerns the second part of our classification. The problem types (models) are discussed in Section 4.

3.1 Methodology of the papers

Figure 1 shows the use of various research methodologies that were applied to stochastic multi-echelon inventory systems. There is no clear trend in the preference for a particular methodology over time. Discrete event simulation as an optimization method starts in the early 1990s. A plausible explanation is that the computing power needed to optimize multi-echelon inventory systems by simulation was not available

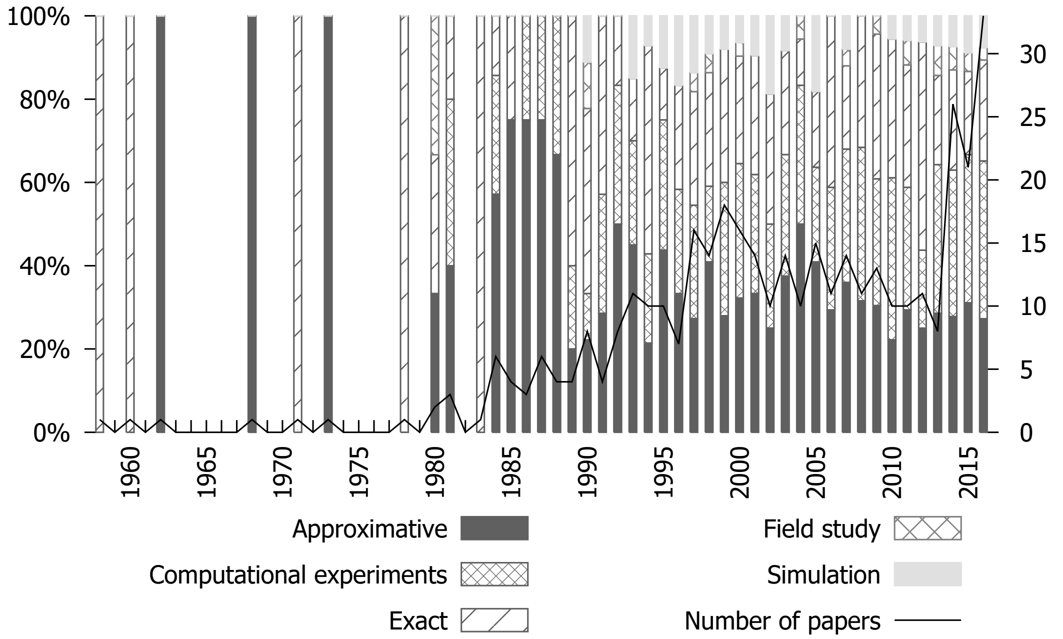

Figure 1: Methodology

before that point in time. As computers get faster, this methodology holds a promise for optimizing policy parameters for large-scale realistic systems.

The fact that 56% of the papers develop approximate expressions for performance measures shows the complexity of the analysis of multi-echelon inventory systems under stochastic demand. We have classified papers under the balance assumption and under the GSM assumption as exact if starting from these assumptions no additional assumptions were used that made the analysis approximate. Clearly, both the balance assumption, which relaxes the constraint that order release quantities must be non-negative, and the GSM assumption, which either strictly bounds demand or assumes unspecified flexibility to always satisfy stochastic demand, are assumptions that depart from reality. In the case of the balance assumption, various papers assess the impact of the relaxation on the validity of the mathematical analysis by discrete event simulation (Diks and de Kok 1999; Doğru, de Kok, et al. 2009; van der Heijden et al. 1997; Zipkin 1984). Exact analysis is presented in 44% of the papers. In 12% of the papers, discrete event simulation is used as the basis for optimization.

One striking insight derived from this count is that the number of papers documenting field studies is small for a field that claims to have a wide range of real-world applications.

3.2 Research goal

The research goal of most publications is optimization (see Figure 2) in order to facilitate decision support. Earlier and seminal contributions determined optimal policy structures, whereas performance evaluation received more attention in later years, in particular in the 1990s. As more concepts and approaches evolved over time, comparisons were needed.

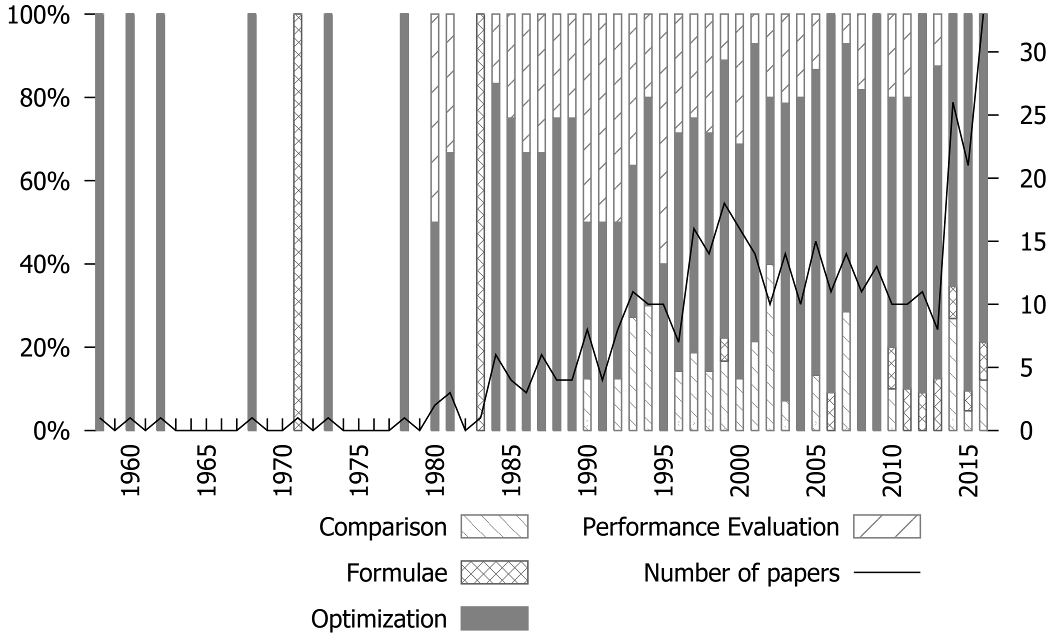

Figure 2: Research goal

3.3 Applications in practice

We found only a few field studies: less than 5% of the classified papers discuss an actual application of the methods in a real-world setting, which we classify as "Field Study" in the methodology dimension. Given this small number, and given the importance of the application aspect for supply chain research, it is worthwhile to briefly discuss these papers in more detail.

Overall, the application cases roughly fall into two types of business processes: managing service parts on the one hand and managing inventory through the manufacturing chain for either industrial or consumer products on the other hand. One exception is Cachon and Fisher (1997), who optimize reorder points in the distribution supply chain from warehouses to retailers in a vendor-managed inventory setup for Campbell Soup.

The first applications were reported by Muckstadt and Thomas (1980) for an anonymous industrial system and by Cohen, Kamesam, et al. (1990) for IBM's US after-sales service business. Both address the configuration of the parts distribution network, including a non-centrally controlled supply chain or the value of considering a multi-echelon versus single-echelon model in order to quantify the inventory required for given service levels. Another application at IBM, this time as part of a larger, extended-enterprise strategic decision-support system that considers production materials, finished goods and service parts, is reported in Lin et al. (2000).

Another set of papers, from Graves, Kletter, et al. (1998) including Billington et al. (2004), Bossert and Willems (2007) and Schoenmeyr and Graves (2009) up to Farasyn et al. (2011), all consider strategic safety stock placement based on the guaranteed service model (GSM). To some extent, they represent the development of the GSM model over time, both conceptually and with respect to its dissemination through commercial off-the-shelf inventory management tools. The applications are all in the area of manufacturing for either consumer goods (Kodak, HP, Procter and Gamble) or industrial products (Celanese, Teradyne). Most of these papers have been published in the journal Interfaces.

In de Kok et al. (2005a) dynamic echelon base-stock policies as a basis for operational control of the supply chain of Philips Semiconductors and its downstream partners eliminate the bullwhip effect. The instantaneous calculation of material-feasible plans is a distinct feature that comes with the application of base-stock policies from multi-echelon inventory systems under stochastic demand. Normally, computationally intensive mathematical programming heuristics are used for this purpose that do not allow for testing the impact of human overwrites during planning sessions involving multiple actors in the supply chain.

More recent papers look at different, more particular and more diverse aspects of supply chain and inventory system. Yang et al. (2013) investigate the value of lateral transshipments and pipeline stock for service parts of industrial (dredging) products. Moncayo-Martinez, Resendiz-Flores, et al. (2014) use the GSM model for strategic safety stock placement for an unnamed company in the automobile parts industry, while Klosterhalfen, Minner, and Willems (2014) combine the GSM model with dual sourcing aspects for an unnamed client in the industrial electronics industry.

Recently, the application areas have become more diverse. Berling and Marklund (2014) consider the distribution supply chain in the retail field, showing that a coordinated inventory policy can significantly reduce inventory investment while increasing service levels, using continuous review (R, nQ) policies. van den Berg et al. (2016) look at inventory allocation for service parts in the utility industry, where the service level quantification goes beyond the usual parts-based measure to capture the resulting unavailability in terms of relative minutes of downtime for the utility's clients. Doğru and Özen (2015) look at tactical inventory planning in the telecommunications equipment industry. Fleischhacker et al. (2015) study inventory positioning of pharmaceutical products in a clinical trials supply chain, which is by its nature a finite horizon problem. They use a stochastic programming model with chance constraints to determine the initial inventory as well as base-stock levels.

Overall, the reported savings are usually huge for the reported applications, in the multi-million dollar range or more. The applications typically involve large business transformation and organizational change projects. Such projects do not happen very often, which might be one reason for the rather small number of published field studies. Most likely, the adoption of supply chain and inventory research results in practice is much more common than the few cases reported in the literature suggest due to confidentiality or other constraints.

4 Problem types studied in the papers

In this section, we specify which types of problems have been studied and what the main achievements have been. We structured this following the dimensions of our typology. Since papers may study several problem types at the same time, the sum of percentages of type classes may exceed 100%. For each dimension, we identify avenues for further research. This research should close the gap between the assumptions made so far and the assumptions required for application of the models developed in real-life situations.

4.1 Number of echelons

As we consider *multi*-echelon inventory systems under stochastic demand, it is of interest how many echelons the systems studied in literature consist of. We find that roughly 62% of the papers consider two-echelon systems and 39% of the papers consider n-echelon systems. Of the latter papers, 15% concern convergent systems, 41% concern serial systems, 22% concern divergent systems, and 31% concern general systems. Of the papers on general n-echelon systems, about 24% assume bounded demand. We can conclude that the majority of papers is on two-echelon systems, which shows that extending the analysis to more than two echelons is by no means trivial. We need specific assumptions like bounded demand or the balance assumption of Eppen and Schrage (1981) to allow for the analysis of n-echelon general structures. Otherwise, due to the curse of dimensionality, an approximate analysis of n-echelon systems seems inevitable.

As the number of echelons in a supply chain is primarily determined by the number of levels in the Bill of Material of the product family under consideration, two-echelon supply chains are seldom. Thus, it is important to pursue further research on n-echelon systems, where we identify policies that allow for mathematically tractable results or simulation-based optimization.

4.2 Structure

Considering the structure of the supply chain, it comes as no surprise that the first papers on multi-echelon inventory systems concern serial structures, e.g., Simpson (1958) and Clark and Scarf (1960). Muckstadt (1973) introduces a general many-to-many structure in the context of repairable products and components. The paper by Lambrecht et al. (1984) is the first on convergent structures, inspired by inventory management with MRP systems. For both structures, there is an increasing number in the following years, especially in the 2000s.

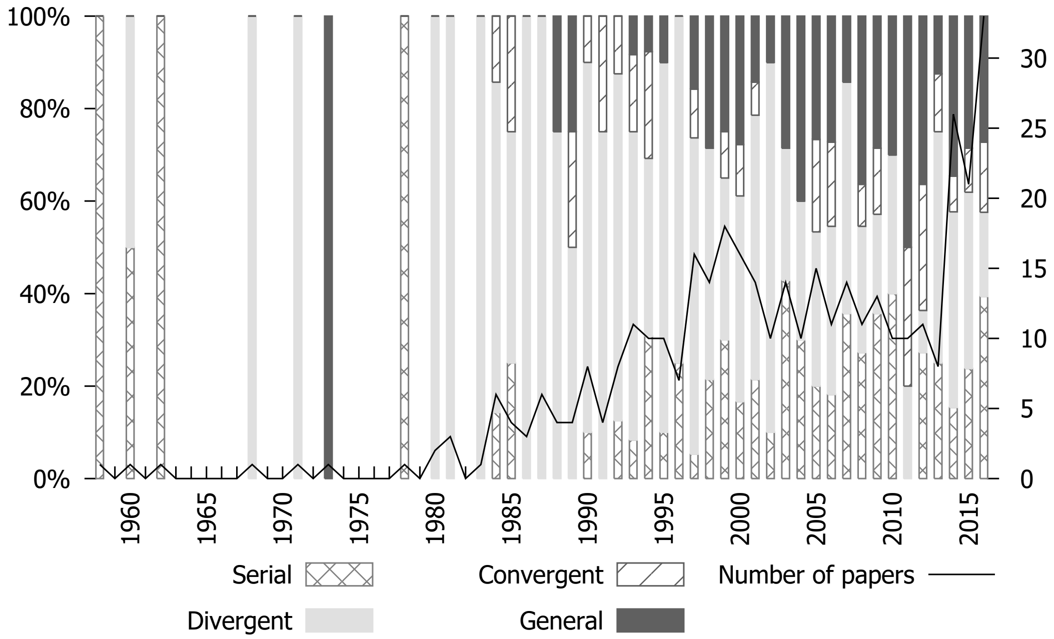

Figure 3: Structure

Clark and Scarf (1960) provide the methodological foundation of much of the work on multi-echelon inventory systems, as the convexity arguments they used to prove optimality of base stock policies and the recursive determination of optimal base stock levels has been used in many subsequent papers. Roughly 23% of the papers classified concern serial systems. Until 1980, divergent systems were considered together with serial systems, mainly in continuous time and in the context of repairable items. Eppen and Schrage (1981) initiated two decades of papers on divergent systems with major contributions in the 1980s from Federgruen and Zipkin (1984a,b,c) and

Zipkin (1984). Rosling (1989) published his seminal paper on convergent systems in discrete time, showing the equivalence with serial systems. Interestingly, papers on convergent structures only concern 11% of the papers we classified.

Around the turn of the century, Assemble-To-Order (ATO) systems consisting of two BOM levels and a general structure, i.e., a component can have multiple parents and an end-product can have multiple children, become the focus of attention, see Chen and Song (2001), Song (1998), and Song, Xu, et al. (1999).

We find three different methods for analyzing general n-echelon systems. Ettl et al. (2000) determine the system performance under installation base stock policies and optimize the base stock levels by a tailor-made conjugate gradient method. de Kok and Visschers (1999) extend Rosling (1989) to general structures, which yields a class of echelon base stock policies called Synchronized Base Stock (SBS) policies (de Kok and Fransoo 2003), for which the optimal parameters can be determined efficiently (using results from Diks and de Kok (1999)).

Inderfurth (1991), Inderfurth and Minner (1998), Graves and Willems (2000), and Humair and Willems (2006) extend the work by Simpson (1958) to more general structures and this work marks the start of a huge amount of papers on general structures under the guaranteed service model (GSM) assumption. A second push for the GSM was triggered by Magnanti et al. (2006). They presented a mixed-integer linear programming model (MILP) for the (approximate) solution of the GSM in very general contexts. This step enables the treatment of the GSM by standard MILP solvers.

As, in practice, serial systems do not exist, the progress made since 1990 on divergent structures and general structures is of paramount importance. Still, more research on general structures is needed as the assumptions made regarding demand processes, lead times and lot-sizing are restrictive.

4.3 Time

Throughout the entire history of stochastic multi-echelon research, roughly 50% of the papers assume discrete time, that means 50% of the papers assume continuous time. Discrete time assumptions are motivated by the underlying planning systems, such as MRP. The continuous time assumptions are motivated by the fact that user and customer demands trigger replenishments. From the beginning, both continuous and discrete time are used and no trends over time can be identified. The continuous-time papers are dominated by spare parts management, starting with the seminal paper of Sherbrooke (1968). The discrete time papers build on the work by Clark and Scarf (1960). GSM papers play a special role, starting with Simpson (1958). Although Simpson (1958) uses continuous time formally, the same modeling approach could be formulated for discrete time by just requiring the service times to be integral.

This was actually exploited in the dynamic programming algorithms introduced by Inderfurth (1991).

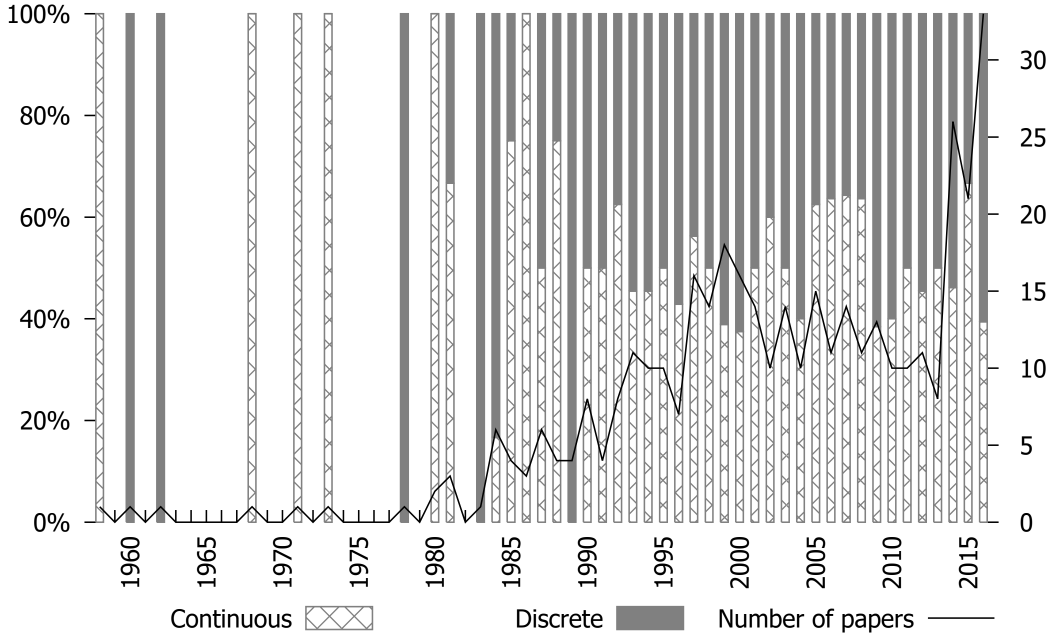

Figure 4: Time

When considering real-life situations, we can distinguish between the continuous time *service* supply chains, i.e. spare parts systems, and the discrete time *initial* supply chains, i.e. supply chains that create products. Due to the low demand rates in service supply chains and the many sources of demand, it is quite natural to assume continuous time demand-driven policies and Poisson demand. Many real-world aspects of service supply chains, such as transshipments and expediting, have been dealt with. This explains the success of quantitative models for service supply chains embedded in software since Sherbrooke (1968). The situation for initial supply chains is much different. The discrete time characteristics of the models comes with the fact that these supply chains are to a large extent forecast-driven. Decisions on order releases are taken weekly or daily, as order release requires careful coordination between different links in the supply chain. Control of initial supply chains is to a large extent still MRP-logic-based, despite its fundamental flaws as explained in de Kok and Fransoo (2003). The aforementioned software tools for multi-echelon system optimization are mainly used to set safety stock parameters in MRP. An exception is the implementation of the SBS policies at Philips Electronics as discussed in de Kok et al. (2005a). Hence, development of discrete time policies for operational control of general structures under demand and supply uncertainty is a prerequisite for further progress.

4.4 Information

Almost all papers assume global information (cf. Figure 5). This might be surprising at first sight, but it is a consequence of our convention to also categorize installation stock policy papers, which require global information to set coordinated parameters as global. For the identification of those contributions that only require local information for replenishment execution, we refer the reader to the policy classification into echelon and installation stock types. Although supply chain research has seen a large number of contributions on gaming and information issues over the last decade, there is still a research gap with regard to complex supply networks that go beyond two-stage serial systems or the analysis of contractual coordination problems without inventories or in single-period environments.

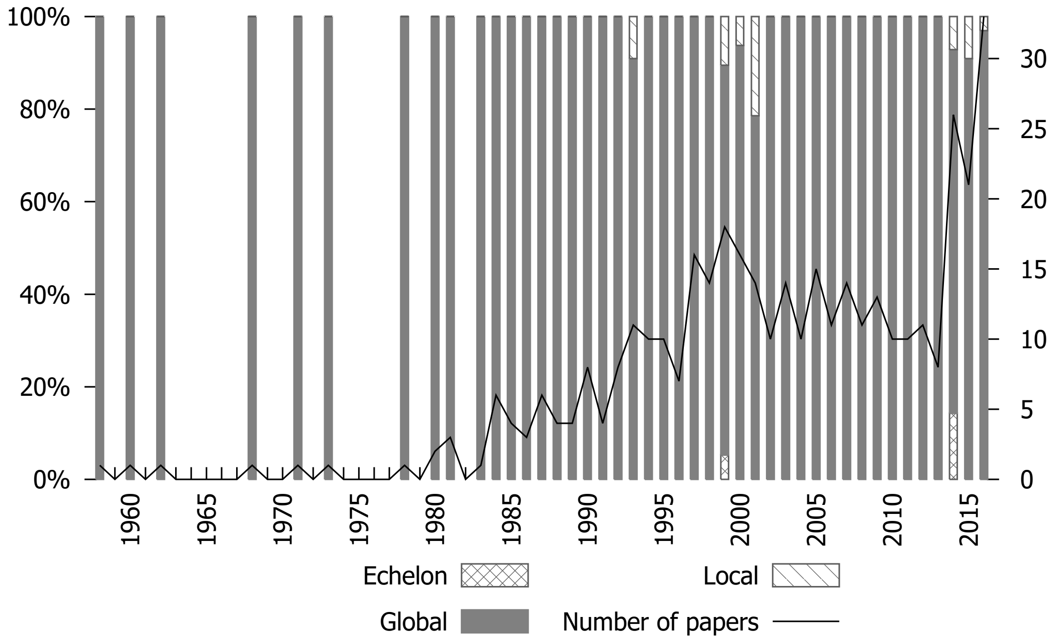

Figure 5: Information

4.5 Capacity

Early papers only considered systems with infinite capacity. The first paper assuming finite capacity by Lee and Moinzadeh (1987b) considers a service supply chain with finite repair capacity. From the beginning of the 1990's and onwards, papers assuming finite capacity were consistently published, but the majority of publications still uses infinite capacity, see Figure 6.

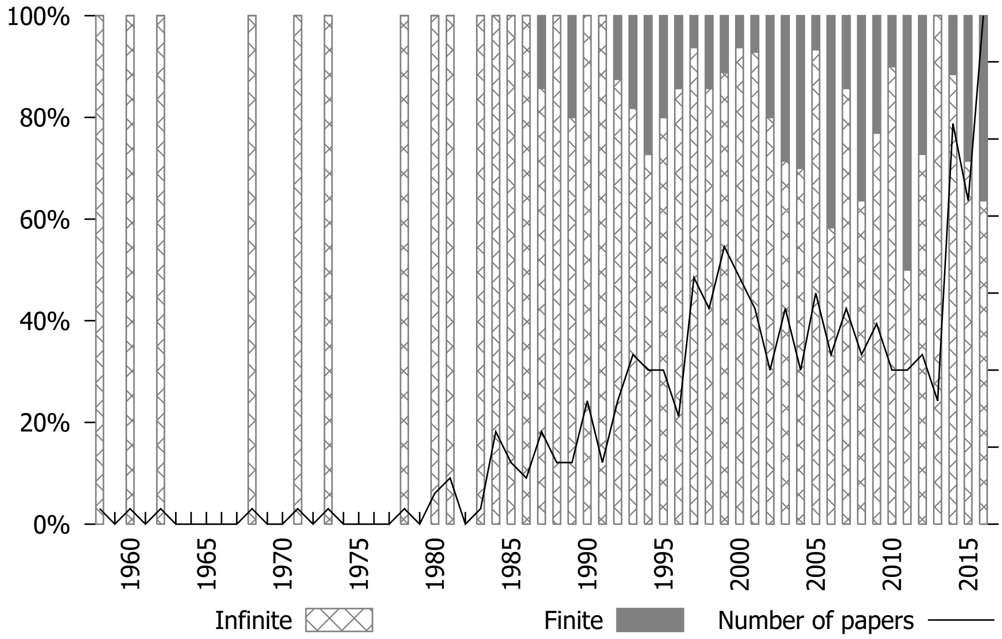

Figure 6: Capacity

Similar to lot-sizing, which is discussed later, finite capacity adds considerable complexity to multi-echelon inventory system optimization under stochastic demand. To date, there are no analytical results that enable calculation of (close-to-)optimal policies under finite capacity across a multi-echelon system. Assuming base-stock policies and finite capacity, Glasserman and Tayur (1994) and Glasserman and Tayur (1995) circumvent this analytical barrier by applying the Infinitesimal Perturbation Analysis (IPA) technique to sample paths from discrete event simulation to numerically compute gradients of the cost function as a function of base-stock levels.

It seems that the assumption of finite capacity at the most upstream system node (in the case of serial and divergent systems) does not add complexity in terms of determining an optimal policy compared to the infinite capacity case. However, as soon as we consider finite capacity at other nodes in the network, no results are available. Janakiraman and Muckstadt (2009) identified the structure of the optimal policy for capacitated serial systems, yet the structure of the policy is high-dimensional and intractable for practical purposes.

The complexity of the analysis of n-echelon models is due to the mutual dependencies between echelon inventory positions and echelon stocks of different items at different points in time. In the case of infinite capacity serial systems these mutual dependencies can be expressed in a set of recursive equations that link the inventory position of an item to the echelon stock of its predecessors: the inventory position of an item at any point in time is bounded by the echelon stock of its predecessor at the same point in time. These recursive equations are generalized to the case of divergent n-echelon systems in Diks and de Kok (1998) under the balance assumption (cf. Eppen and Schrage (1981)). However, when assuming finite capacity in serial systems, under echelon base-stock policies the mutual dependencies propagate over time, so that the inventory position of an item at some point in time depends on the echelon stock of its predecessors over multiple points in time in the past. Thus we loose the Markov property that it suffices to know the state of the system at the time of decision-making. This phenomenon of dependence of item inventory position on the evolution of the echelon stock of its predecessor over time also occurs when analyzing random yield in multi-echelon systems. It also explains why, except for papers on serial systems, most papers only assume two-echelon systems: complexity increases considerably with the extension from two to n-echelon systems. In view of the above, it comes as no surprise that more than 80% of the papers assume infinite capacity. We do see increased attention to finite capacity systems in the last three decades: from about 5% before 1990 to 25% since 2010. Furthermore, we note that about 55% of the finite capacity papers assume constant delays and about 30% assume exponential delays. Among the latter, we see both convergent and divergent systems, while in the former, we primarily see serial and divergent systems.

In real life, there is no such thing as infinite capacity. Despite the fact that lead time agreements can be made, such that anything ordered can be delivered within the agreed lead time, we need more insight into the impact of the dual constraints set by both resource and material availability. Concerning multi-echelon inventory models that assume finite capacity, we conclude that Janakiraman and Muckstadt (2009) provide the state-of-the-art regarding discrete time systems. The discrete time systems best represent the operational decision problem that has been supported by MRP systems since 1970. As Janakiraman and Muckstadt (2009) consider only serial systems, we need further research on capacitated convergent and capacitated divergent systems before we can make the leap towards general capacitated systems. Regarding finite capacity systems in continuous time, Abouee-Mehrizi et al. (2014) explicitly model finite capacity as an M/G/1 queue, while most papers so far now model finite capacity assuming exponential production (throughput) times, which essentially still represents infinite capacity. So, also for continuous time systems, finite capacity multi-echelon inventory systems require substantial research efforts to make real progress in understanding supply chain behavior.

4.6 Delay

Delay is the time it takes for an order to get from the supplier to the customer, production time included, stock-out delays excluded. When considering the assumptions concerning the delay of replenishment orders, 76% of the papers assume constant delay, see Figure 7.

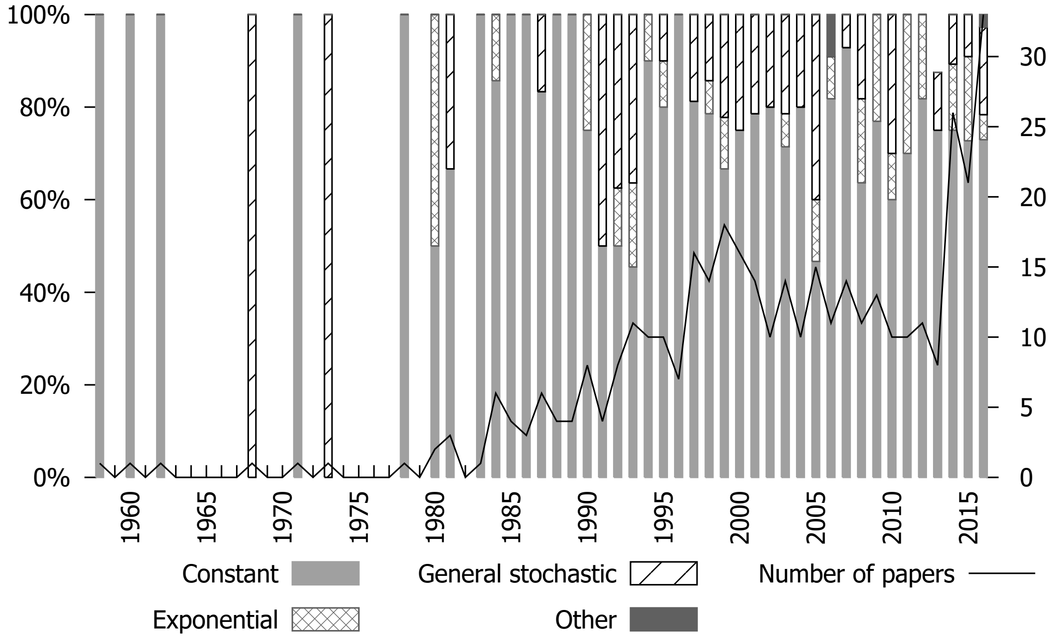

Figure 7: Delay

We find that an exact analysis usually assumes either constant delay or exponential delay. Under the latter, we find that the memoryless property of the exponential distribution allows for Markov decision process (MDP) formulations and the application of quasi-birth-death processes. The constant delay assumption ensures non-overtaking of orders, which is another assumption that underlies the tractability of analysis. In most cases, stochastic delays imply the assumption of continuous time control. Apparently, general stochastic delays induce considerable mathematical challenges, as only 23% of the papers assuming this provide an exact analysis. Furthermore, exponential delays are often assumed for tractability, after which, e.g., discrete event simulation studies show insensitivity of the results when non-exponential delays are considered. The seminal paper on spare parts systems by Sherbrooke (1968) was the first to exploit this insensitivity for spare parts distribution systems.

Like in the discussion concerning time, we should distinguish between service supply chains and initial supply chains when considering future research related to the delay dimension. In service supply chains, the quasi-birth death representation of the system allows for an incorporation of stochastic delays. Numerical methods are available to solve large-scale systems. The insensitivity results we found allow for the assumption of exponential delays, which reduces the state space. In initial supply chains, the combination of discrete time decision making and stochastic delays pose a major challenge for mathematical tractability. It is of great importance to make progress here as we need to develop a better understanding on how to operationally control multi-echelon systems for initial supply chains under stochastic delays.

4.7 Demand

The assumptions about the demand process (see Figure 8) are often essential for tractability. The assumption of Poisson demand is natural for spare parts systems (rare event perspective) and low quantities. We find that 32% of the papers assume Poisson demand and an additional 10% compound Poisson demand. The assumption of Upper Bounded Demand in the recent (since 2000) GSM papers explains the high (15%) percentage over the last two decades. About 35% of the papers assume general stochastic demand. Of these papers, over 75% assume discrete time and constant delays. This can be explained by the observation that, under discrete time and constant delays and assuming a convenient control policy, exact expressions for costs and service can be derived for serial and divergent systems. Another observation is that the normal distribution is often used as an approximation for a general distribution.

Most initial supply chains are forecast-driven, which implies that control parameters are updated weekly or monthly. There is virtually no paper that rigorously treats such situations. The stream of research on the bullwhip effect (cf. Wang and Disney (2016)) takes updating of the control parameters into account, which is probably the main source of the bullwhip effect. Yet the analysis in this stream of papers is not entirely rigorous, as upstream availability constraints are not taken into account when setting control parameters. The impact of explicitly taking into account upstream availability constraints is demonstrated in de Kok (2012), who shows that the bullwhip returns in the form of highly variable shipment quantities to the most downstream level, which requires a substantial increase in downstream safety stocks to maintain the required service level. Explicitly taking into account forecast errors is challenging, even for single-echelon models. Clearly, here is a subject of research awaiting further foundational contributions.

4.8 Customer response to stockouts

The first paper by Simpson (1958) used a guaranteed service approach, but in the following years only backorder type customers were considered. The majority of

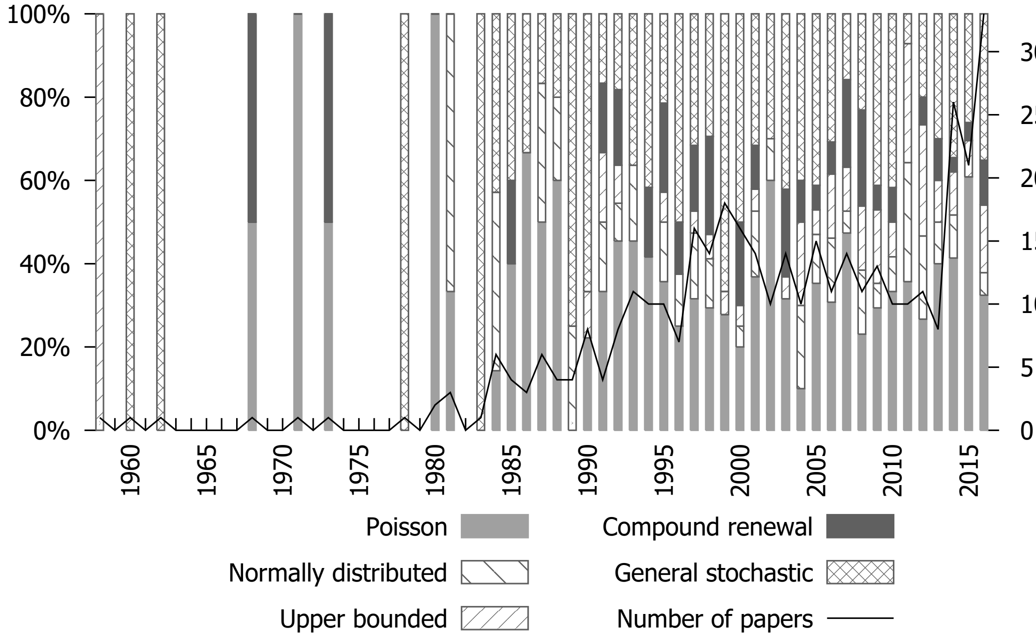

Figure 8: Demand

publications over time uses this type of customer behavior, see Figure 9. In the early and mid 1990s, guaranteed service models reappeared and the concept of lost demand was introduced.

Tractability is again the reason why 82% of the papers assume backordering of demand that cannot be satisfied in time. Optimal policies are only known under the assumption of backordering. In 10% of the papers, the guaranteed service assumption is made, which implies that all demand is satisfied. This is realized by assuming upper bounded demand or some unspecified flexibility in supply. In 11% of all papers, demand not met in time is lost. In over 55% of these papers, demand is assumed to be Poisson. Lost-sales models received more attention in the 2010s as the share increased to 17%.

In practice, customer responses to stockouts vary. In business-to-consumer (B2C) environments, most customers choose another product or another retailer. With online sales, this has become easier than before. In business-to-business (B2B) a delivery time is negotiated when products are not available on time. If the proposed lead time is too long, the customer may still renege, otherwise the customer accepts the longer lead time. Thus, the demand process is impacted by the reneging behavior of the customers. Any form of reneging is likely to increase the state-space of the underlying Markov Decision Process to be solved, like with lost-sales for single echelon models. As it is not likely that a particular nice optimal policy can be found, it seems

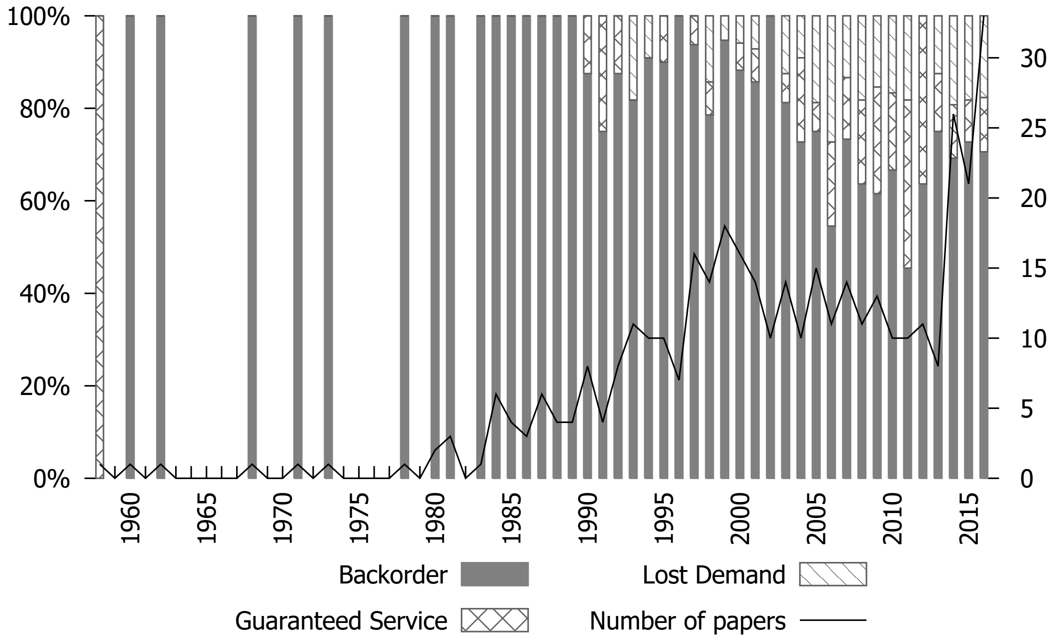

Figure 9: Customer

that the route to go is to propose classes of policies that allow for tractability, along with assumptions on the demand process and delay process, such as exponential or phase-type distributions, so that exact or approximate performance analysis is within reach. Managerial insights may be gained through carefully designed simulation experiments.

4.9 Policy

Remember that the specification of a policy class means that only policies in this class are considered. Whenever no policy class is prescribed, researchers seek an optimal or close-to-optimal policy. Some of the prescribed policy classes like base-stock policies *happen to be* the result of a search for an optimal policy. This has to be distinguished from the case where the search has been restricted to a particular class from the beginning.

4.9.1 Optimal policies

As in most other areas in the field of stochastic processes, researchers have strived to find optimal control policies. In the field of inventory management, it is commonly assumed that costs for holding inventory are linear in time and number on hand, while penalty costs are linear in time and number of backorders. Besides holding and penalty costs, fixed order costs are considered. Though other objective functions have been considered, we restrict ourselves to this cost structure, as it concerns the vast majority of papers devoted to the quest for optimal policy structures. In our analysis, we distinguish between serial, convergent, divergent and general structures.

For n-echelon serial systems, Clark and Scarf (1960) prove the optimality of echelon order-up-to policies under constant delays and discrete time for both the average cost case and the discounted cost case without fixed costs. In Clark and Scarf (1962), this result is extended to systems with a fixed cost at the upper echelon only. The stochastic delay case is proved by Muharremoglu and Tsitsiklis (2008) under the assumption that subsequent orders do not overtake and demand is discrete. For serial two-echelon capacitated systems, Parker and Kapuscinski (2004) prove that, if capacity at the downstream echelon is smaller than at the upstream echelon, a modified base stock policy is optimal for both stages. They observe that a so-called push-ahead effect is caused by a *disguised* base-stock level that cannot be achieved due to capacity limitations when the echelon-inventory position at the downstream stage is low, but can be reached if the inventory position at the downstream stage is high enough. For serial n-echelon capacitated systems with identical capacity limits at all stages, Janakiraman and Muckstadt (2009) characterize the optimal policy as a multi-tier base stock policy.

For n-echelon convergent systems with constant delays and no fixed ordering costs, Rosling (1989) proves that echelon order-up-to-policies are optimal and under these policies each convergent system is 1-1 related to a serial system. For n-echelon divergent systems with constant delays and no fixed ordering costs, Diks and de Kok (1998) show that echelon-order-up-to policies are optimal. However, this can only be shown under the assumption that negative shipment quantities to downstream stockpoints are allowed. This assumption was first proposed by Eppen and Schrage (1981). The implication is that echelon inventory positions after allocation can be lower than before the allocation, i.e., the option of free transshipments. As a consequence, the classical inventory balance equations for individual items may no longer hold. So far, it has been impossible to identify well-structured optimal policies for n-echelon divergent systems without this assumption.

For n-echelon general structures, there are no results on optimal policies. Various authors identified optimal policies for special general structures. Nadar et al. (2014) and Benjaafar, ElHafsi, et al. (2011) show that state-dependent order-up-to policies are optimal under multiple discrete demand classes and exponential delays, and that an optimal allocation is based on critical levels. These results have been developed only for two-echelon systems, mostly under the heading of Assemble-To-Order systems. For Assemble-To-Order systems in discrete time, Reiman and Wang (2015) derive asymptotically optimal policies using a stochastic programming approach.

As indicated in Section 4.5, major challenges regarding optimal policies concern systems with finite capacity. It is fair to say that, for general structures there is no hope to find optimal policies under discrete time and constant lead times. The recently proposed stochastic programming approaches seem to lend themselves to application in the capacitated case. Research on the robustness of results under assumption of exponential delays, allowing for overtaking of orders, may lead to more extensive application of this assumption to initial supply chains, similar to its application to service supply chains. Another obvious avenue for identifying optimal policies concerns lot-sizing. Most results obtained so far relate to models without fixed costs. We discuss this more extensively in Subsection 4.10.

The above discussion implicitly assumes that demand is modeled as some stochastic process. A departure from that assumption is the GSM assumption, a notion coined by Graves and Willems (2000). The model under the GSM assumption was originally proposed by Simpson (1958). Under this assumption, optimal installation base stock policies can be derived computationally, as the optimization problem can be formulated as a concave programming problem. In our classification, we have indeed classified the solutions from models under the GSM assumption as optimal. On the other hand, optimality of a solution should be viewed in the context of the application of the model. The bounded demand model proposed by Simpson (1958) is different from the stochastic demand model proposed by Clark and Scarf (1960) and yields different solutions for optimal inventory deployment. This suggests the need for further research: i) Comparisons of different model paradigms on an identical set of benchmark problems, the data of which not necessarily meet all technical assumptions of the models, and ii) field studies where the empirical validity of the modeling assumptions can be assessed.

4.9.2 Predetermined structured policies

Figure 10 shows the development from few to many different policies over time. Initially, installation base-stock was popular or no policy was prescribed at all, i.e., the optimal policy was left to be determined in the research. Starting in the 1980s, more different policies that use the concept of echelon stock were introduced. 61% of the papers assume installation stock policies, whereas only about 16% assume echelon stock policies. The remaining papers either leave the policy subject to analysis or assume other policies.

Close to 16% of the papers derive an optimal policy under various assumptions. It seems that this percentage has remained stable over the last three decades. In more than 50% of the papers, a base stock policy is assumed, 21% assume (s,nQ)-policies and only 3% assume (s,S)-policies. This is another indicator for the complexity of multi-echelon inventory systems under stochastic demand. Under base stock policies, the customer demand propagates unchanged upstream, both in timing and quantity,

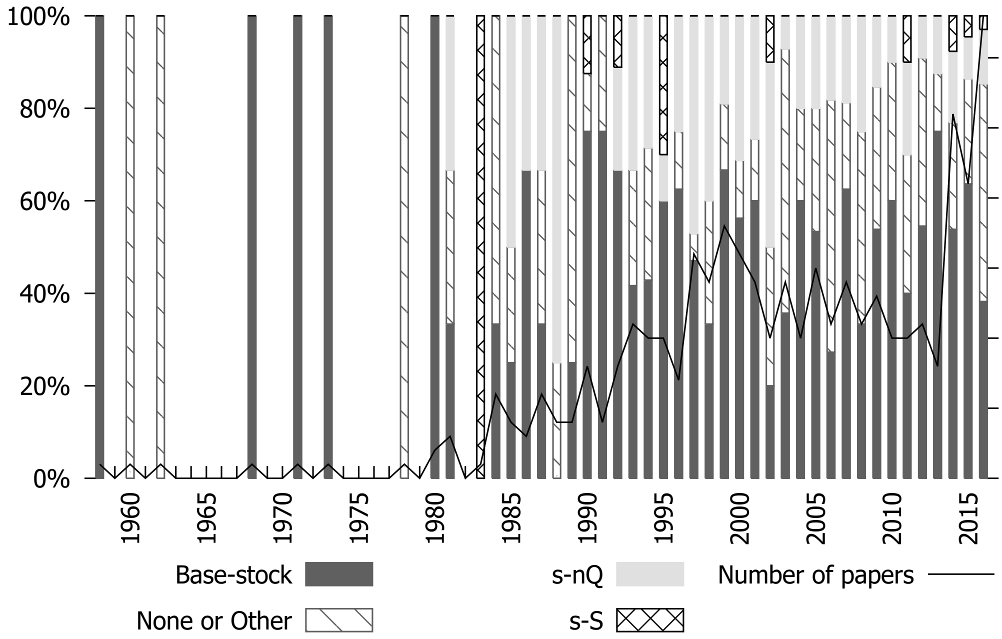

Figure 10: Policy

possibly in an aggregate form, e.g., when considering divergent systems. This is a cornerstone for the analysis of multi-echelon systems. As soon as lot-sizing or lost sales are assumed, the demand process at upstream echelons is affected in a more or less complicated manner.

We expect that pre-determined structured policies are the means to obtain scientifically and practically relevant results. Such policies should enable computationally tractable results, be it by using simulation or mathematical analysis or both, while at the same time ensuring close-to-optimal results. We expect that this is a rewarding direction as it requires both sophisticated mathematical analysis aimed at providing error bounds and sophisticated algorithms to cope with the natural structural complexity of supply chains.

With regard to policy structures, in order to operate a supply chain, we need formal order release rules, that take material and resource constraints into account. For example, the GSM model allows for calculating safety stock levels, but provides no indication how to resolve operational issues when material limits satisfaction of production requirements. Thus, research is needed to identify control mechanisms that enable operational control of general structures and to assess their performance. An interesting class of policies is that of rolling schedule policies derived from solving deterministic or stochastic finite horizon mathematical programming problems.

Another route towards identifying effective operational control rules for general structures is in line with the recent research on N, W, and M-models by Nadar et al. (2014), Nadar et al. (2016), and Lu, Song, and Zhang (2015). The basic structures and some additional assumptions allow for finding an optimal policy structure. These policy structures may be extendable to general n-echelon systems and are computationally tractable. This direction of research is both challenging and of great importance.

4.10 Lot-sizing

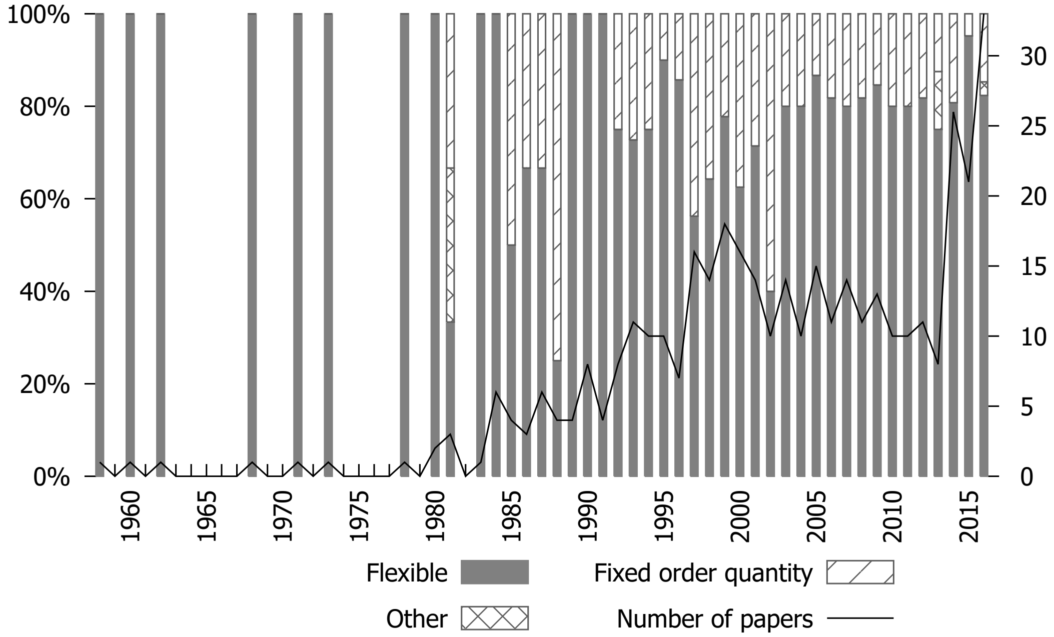

Figure 11: Lot-sizing

Lot-sizing has been a primary research subject in the context of multi-echelon systems under deterministic demand. Apparently, under the assumption of stochastic demand, lot-sizing, i.e., assuming that demand is batched into a lot to reduce the order-related costs over time, makes the analysis much harder. This is due to the fact that, under stochastic demand and fixed lot sizes, the timing of orders becomes general stochastic. Even under Poisson demand, lot-sizing induces Erlang distributed times between ordering, the renewal character of which does not "fit" with discrete time models and constant delays. We found that 80% of the papers assume no lot-sizing restrictions, see Figure 11. This includes the papers that derive the optimal policy structure, which are about 30% of all papers. About 50% of the papers assume base stock policies, either installation stock or echelon stock. Of the papers assuming fixed order quantities, almost 90% assume a serial or divergent structure. Both serial and divergent structures imply sequential decision making over time, while convergent structures imply parallel decision making over time. As stated above, the stochastic timing of orders when using fixed lot-sizing makes the analysis of convergent structures extremely difficult. Finally, 80% of the fixed order quantity papers assume continuous time. Flexible lot-sizing is dominant and was exclusively used until the 1980s. Subsequently, fixed order quantities were assumed in de Bodt and Graves (1985) and Schwarz et al. (1985).

When considering future challenges for research on lot-sizing in multi-echelon inventory systems under stochastic demand, we should carefully look at the typical cost structure in today's supply chains. Moving upstream in the chain, capital intensity tends to increase, whereby asset utilization becomes a major driver of profits. With high utilization comes the need for lot-sizing. We found that papers with exogenous lot-sizing constraints are few. Papers assuming lot-sizing constraints typically assume some form of nesting, i.e., upstream orders are triggered by downstream orders. To see the implication of this nesting assumption in general multi-echelon inventory systems, let us take a closer look at Rosling (1989). He shows that a convergent multi-echelon systems, i.e., an assembly system, without lot-sizing constraints is equivalent to a serial multi-echelon system. This result can be understood when realizing that the echelon inventory position of an item after ordering is the coverage of end-item demand over the sum of its cumulative lead time, i.e., the time from ordering the item until the item as part of the end-item is received in end-item stock, and its review period. The serial system follows from synchronizing each item's coverage with the coverages of items ordered earlier over the item's cumulative lead time plus review period. The analysis in Rosling (1989) can be extended to systems with lot-sizing if we maintain the equivalence with an associated serial system. In serial systems the nesting property comes natural, as it does not make sense to order an item more frequently than its successor. The required equivalence and the nesting property of the serial system implies that an item with a long cumulative lead time is ordered less frequently than an item with a short lead time. In Karaarslan et al. (2013) it is argued that this property does not hold in many supply chains: key components are expensive and have long delays, while non-key components are cheap and have short delays. The Economic Order Quantity finds that the key component has a small lot size and the non-key component a large lot size. This is against the nesting concept. Thus, we need new ideas to develop (close-to-) optimal policies with lot-sizing constraints for real-life situations.

An interesting observation from various empirical studies reported in de Kok (2015) is that upstream inventory has hardly any impact on customer service for the system's end-items. Assuming that large lot sizes create high cycle stocks, it may be possible to decompose the high-lot-size upstream part of the multi-echelon inventory system from the small-lot-size downstream part of the system. Such a decomposition may help to reduce the mathematical complexity of analyzing the system. Yet a thorough theoretical foundation for these findings is still lacking and important to ascertain.

4.11 Flexibility

Apart from Simpson (1958) who assumes that a system is always designed to cope with only bounded and operational flexibility to deal with excessive demands, the early decades see almost exclusively no flexibility (see Figure 12). Flexibility as a concept is introduced at the end of the 1980s and the early 1990s when use of allocation, expediting and routing flexibility begins.

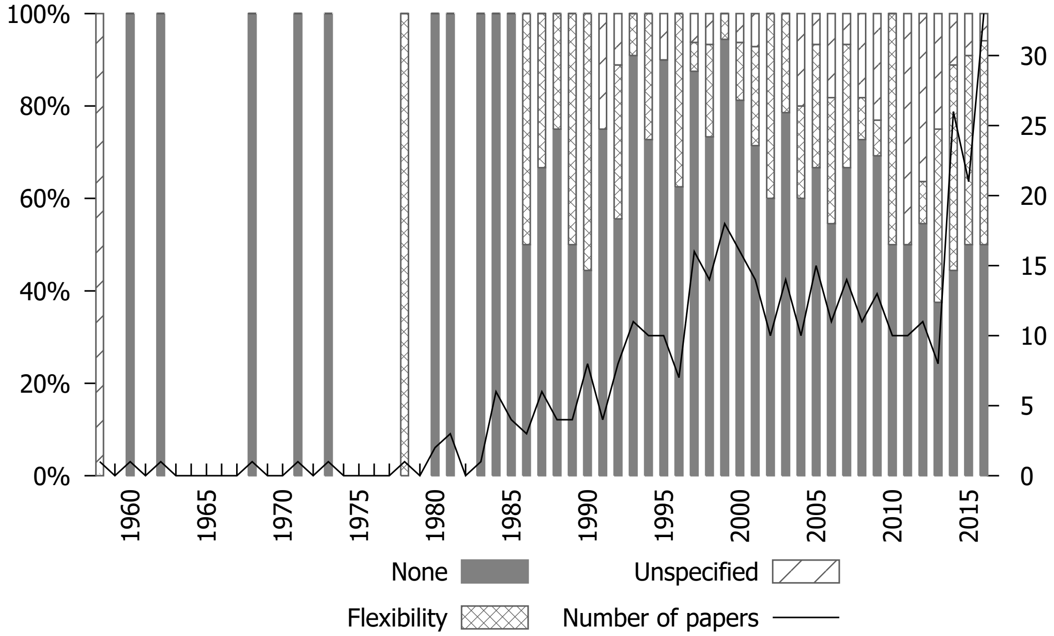

Figure 12: Flexibility

The concept of flexibility has received quite some attention since 2010, as 50% of the papers assume some form of flexibility. We should emphasize that this correlates strongly with the GSM assumption, under which flexibility is assumed, yet no specification of the operational flexibility is provided. Over the entire set of papers, one third assumes some form of flexibility. Out of these papers, 30% assume unspecified flexibility as follows from the GSM assumption, 30% routing flexibility, in particular transshipments, 20% concern expediting, 10% outsourcing, and 20% allocation flexibility. As routing flexibility is mainly about transshipments, divergent structures are dominant under this form of flexibility. We also find that 70% of those papers assume continuous time. This is mainly due to the focus on spare parts systems in this context.

The modeling of flexibility in multi-echelon inventory systems is important: with the growth of online sales and, as a consequence, the emergence of omnichannel supply chains, where a customer order may either be delivered from the brick-and-mortar store or on-line from the DC without the customer being aware of it, we need new models and policies to deal with these complex operational processes. We foresee a mix of dual sourcing and multiple customer classes as modeling ingredients. In the past, flexibility assumptions have enabled the aggregation of inventory and resource availability across multiple locations. This may be a route to pursue further to avoid mathematical intractability. Discrete event simulation can be used to test the assumptions.

4.12 Performance measures

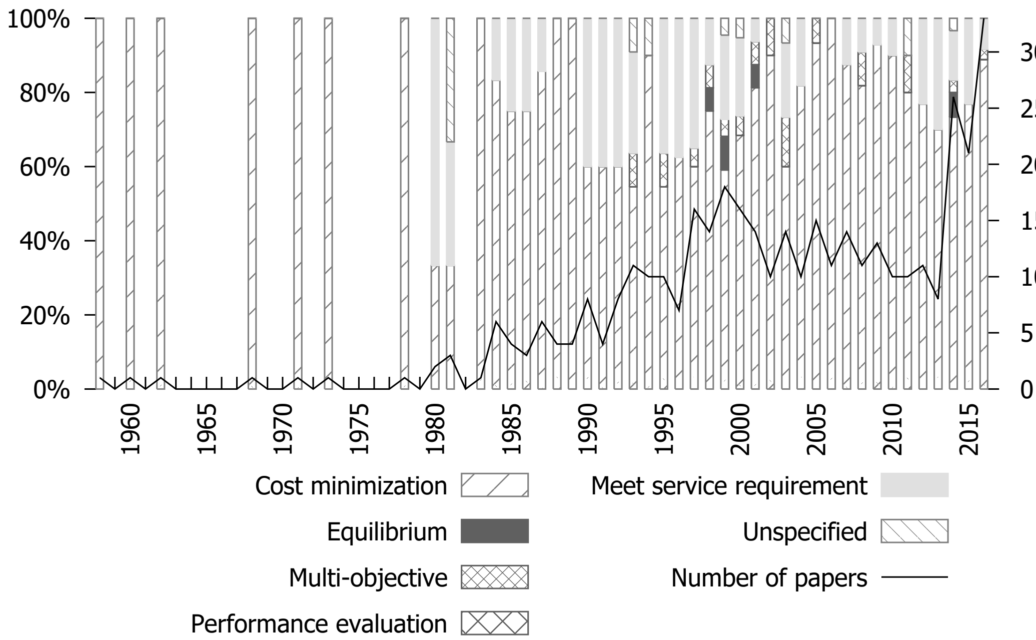

Figure 13: performance indicator

We find that 85% of the papers focus on cost minimization (see Figure 13). This may result into customer service constraints due to Newsvendor fractiles. Later, the objective to meet service requirements was introduced due to requirements of the industry and difficulties with deriving cost parameters for cost minimization, especially for backorders and lost sales. In the 1990s, 27% of the papers concerned performance measures other than cost, which is considerably higher than the 17% share in other decades. This may be due to the stronger focus on computational results for realistic large-scale systems during that period.

In practice, it is often hard to translate the company objectives into a single cost function. In the light of the recent discussion on corporate social responsibility, we suggest research on multiple criteria approaches, trading off costs and service measures and including sustainability measures simultaneously. Furthermore, companies have to take into account risk, which cannot be truly captured assuming an infinite horizon formulation of a cost minimization problem. The causes of risks have gained attention in our field in the form of supply chain disruptions. However, there are not many approaches including this into multi-echelon inventory systems, which are mainly based on stationary conditions, whereas the consideration of disruption would require the optimization of the best transition path back to regular operations. The same holds true for systems that include multiple (backup) supply modes in such systems. Thus, we need research starting from the correct risk modeling and the correct risk mitigation perspective.

5 Conclusions

Based on our classification, we were able to analyze the progress of research on multi-echelon inventory systems under stochastic demand since its emergence at the end of the 1950s. We assessed this progress from the perspective of real-life systems and their characteristics. In this assessment, we made a distinction between service supply chains and initial supply chains.

It is fair to say that Sherbrooke (1968) is the seminal paper that provides the model and the algorithm to determine control parameters in service supply chains. Over the years others have provided a more rigorous analysis of the model in Sherbrooke (1968) and included features of service supply chains that greatly add to their efficiency and effectiveness: transshipments and expediting. The fact that much of the work on service supply chain is now available in software and extensively used in practice should be seen as a great achievement.

Regarding the initial supply chains delivering products to users and consumers, the papers by Glasserman and Tayur (1995) on capacitated systems using Infinitesimal Perturbation Analysis (IPA), Graves and Willems (2000) on the Guaranteed Service Model, Ettl et al. (2000) on the Stochastic Service Model and de Kok and Visschers (1999) on Synchronized Base Stock policies, mark the moment when general structures commonly observed in practice are tackled. The four approaches start from the same model, i.e. general BOM model, nominal lead times, stochastic demand, but differ in assumptions regarding the operational control policy. The ultimate result is that the four approaches may yield different solutions for the same practical situations. This is clearly a topic for further research.

In our assessment of the state-of-the-art, we repeatedly mentioned the use of simulation as a means to tackle the complexity of real-world supply chains. Another important remark concerns the need for the analysis of finite capacity multi-echelon inventory systems. This stipulates the importance of Glasserman and Tayur (1995), who show that their IPA-based methodology applies for such systems. We conclude that extension of Glasserman and Tayur (1995) to systems with lot-sizing, operational flexibility (transshipments, outsourcing, expediting) is a promising direction for further research with great scientific and practical relevance.

We found that the two most cited papers by Lee, So, et al. (2000) and Chen, Drezner, et al. (2000) discuss the bullwhip effect, which is explained by decentralized, self-interested decision making by each link in the supply chain. It is much to our surprise that we hardly found papers that explicitly start from the assumption that information is not shared in the supply chain. Clearly, decentralized installation stock policies are extensively studied. We invariably assume that we can optimize parameters, such as base-stock levels, across the supply chain. Though it allows us to show the potential of centralized safety stock deployment, this perspective does not represent the current state of affairs in most supply chains. We need more empirical research on information sharing, whether strategic, tactical or operational, to provide solid ground for quantitative models that can eventually support effective decision making in real-life supply chains.

Despite its existence since the mid 1950s, multi-echelon inventory systems is still a highly active field of research. Most likely, its complexity and its practical relevance are the reasons for this. No packaged solutions exist. During our classification work we observed that some papers in non-OR journals formulated very general models and used mathematical programming techniques to "solve" the problem. Whenever the inherent stochasticity was not dealt with at least with some form of mathematical rigour, we considered the paper out-of-scope. At the same time it shows that the research on stochastic multi-echelon inventory systems needs to be broadcasted more strongly, as the application of the methods developed in these out-of-scope papers may be unjustified.

We are at the advent of a fourth industrial revolution, denoted as Industry 4.0. The availability of real-time information about location and condition of items throughout the supply chain that is required to implement the echelon base-stock policies shown to be optimal in Clark and Scarf (1960), is now a fact. 3D-printing and the Internet of Things will affect supply chain structures and supply chain planning, execution, and control. We expect that new ways of modeling information states of supply chains will generate a new wave of contributions from the field of multi-echelon inventory systems under stochastic demand. Though information delays are supposed to be reduced to zero, we must be aware that processing materials, repairing machines and shipping containers will always take time, not much different of what we are used to. Multi-echelon inventory models have been the main tool used in order to understand how delays and uncertainty in demand impact supply chain performance. Multi-echelon inventory models and their analysis are the means for an effective implementation of omnichannel retailing, 3D-printing in service supply chains and further collaboration in high-tech supply chains, all of which are to the benefit of the companies and markets involved.

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Graham, R. L., E. L. Lawler, J. K. Lenstra, and A. R. Kan (1979). “Optimization and approximation in deterministic sequencing and scheduling: a survey”. In: *Annals of Discrete Mathematics* 5, pp. 287–326.

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Simchi-Levi, D. and Y. Zhao (2011). “Performance evaluation of stochastic multi-echelon inventory systems: A survey”. In: *Advances in Operations Research* 2012.

Song, J.-S. and P. Zipkin (2003). “Supply chain operations: Assemble-to-order systems”. In: *Handbooks in operations research and management science*. Ed. by A. G. de Kok and S. C. Graves. Vol. 11. Elsevier, pp. 561–596.

van Houtum, G., K. Inderfurth, and W. H. Zijm (1996). “Materials coordination in stochastic multi-echelon systems”. In: *European Journal of Operational Research* 95.1, pp. 1–23.

Wäscher, G., H. Haußner, and H. Schumann (2007). “An improved typology of cutting and packing problems”. In: *European Journal of Operational Research* 183.3, pp. 1109–1130.

A Complete classification of papers through 2016

This appendix provides the classification of all papers that we considered in scope in tabular form. We added the number of citation according to Google Scholar, manually retrieved in July 2017, in order to indicate the impact of the contributions. As was said earlier, some classification could have been decided in another way in some details. Thus, the classification string is our subjective perception of where the main contributions of the respective papers are.

<table>
<tr><th>Reference</th><th>Classification</th><th>Citations</th></tr>
<tr><td>Abouee-Mehrizi et al. (2014)</td><td>2,D,C,EG|F,G|P,B|b,F,A|C||CE,CO</td><td>2</td></tr>
<tr><td>Aggarwal and Moinzadeh (1994)</td><td>2,D,C,G|I,C|P,B|b,F,E|C||AC,O</td><td>48</td></tr>
<tr><td>Agrawal and Cohen (2001)</td><td>2,G,D,G|I,C|GN,B|b,F,N|CS||A,O</td><td>131</td></tr>
<tr><td>Akçay and Xu (2004)</td><td>2,G,D,G|I,C|G,B|b,F,N|C||AC,O</td><td>104</td></tr>
<tr><td>Albrecht (2014)</td><td>2,G,D,G|I,C|P,B|b,F,A|C||AC,CO</td><td>4</td></tr>
<tr><td>Albright and Gupta (1993)</td><td>2,D,C,G|F,E|P,B|b,F,N|S||AC,P</td><td>48</td></tr>
<tr><td>Alfredsson (1997)</td><td>4,G,C,G|I,G|P,B|b,F,N|M||AC,O</td><td>116</td></tr>
<tr><td>Alfredsson and Verrijdt (1999)</td><td>2,D,C,G|I,E|P,B|b,F,R|C||A,P</td><td>236</td></tr>
<tr><td>Al-Rifai et al. (2016)</td><td>2,D,C,G|I,C|P,B|q,Q,N|CS||AC,O</td><td>1</td></tr>
<tr><td>Alvarez and van der Heijden (2014)</td><td>2,D,C,G|I,CE|P,L|b,F,R|S||AC,P</td><td>5</td></tr>
<tr><td>Alvarez, van der Heijden, Vliegen, et al. (2014)</td><td>2,D,C,G|I,E|P,B|b,F,R|CS||ACS,OP</td><td>4</td></tr>
<tr><td>Alvarez, van der Heijden, and Zijm (2015)</td><td>2,D,C,G|I,CE|P,BL|b,F,R|CS||AS,O</td><td>13</td></tr>
<tr><td>Andersson, Axsäter, et al. (1998)</td><td>2,D,C,G|I,C|B,B|q,Q,N|C||AC,O</td><td>46</td></tr>
<tr><td>Andersson and Marklund (2000)</td><td>2,D,C,G|I,G|N,B|q,Q,N|C||AC,O</td><td>99</td></tr>
<tr><td>Andersson and Melchiors (2001)</td><td>2,D,C,G|I,C|P,L|b,F,N|C||AC,O</td><td>72</td></tr>
<tr><td>Angelus and Özer (2016)</td><td>n,C,D,G|I,C|G,B|N,F,E|C||CE,O</td><td>2</td></tr>
<tr><td>Axsäter (1990a)</td><td>2,D,C,G|I,E|P,B|b,F,R|C||AC,P</td><td>343</td></tr>
<tr><td>Axsäter (1990b)</td><td>2,D,C,G|I,C|P,B|b,F,N|C||E,P</td><td>290</td></tr>
<tr><td>Axsäter (1993b)</td><td>2,D,C,G|I,C|P,B|q,Q,N|C||AE,O</td><td>229</td></tr>
<tr><td>Axsäter (1993c)</td><td>2,D,D,G|I,C|P,B|b,F,N|C||E,O</td><td>63</td></tr>
<tr><td>Axsäter (1995)</td><td>2,D,C,G|I,C|B,B|q,Q,N|C||A,P</td><td>28</td></tr>
<tr><td>Axsäter (1997a)</td><td>2,D,C,G|I,C|G,B|Qq,Q,N|C||E,C</td><td>16</td></tr>
<tr><td>Axsäter (1997b)</td><td>2,D,C,G|I,C|B,B|Q,Q,N|C||E,O</td><td>94</td></tr>
<tr><td>Axsäter (1998)</td><td>2,D,C,G|I,C|P,B|q,Q,N|C||ACE,P</td><td>78</td></tr>
<tr><td>Axsäter (2000)</td><td>2,D,C,G|I,C|B,B|q,Q,N|C||E,P</td><td>139</td></tr>
<tr><td>Axsäter (2001a)</td><td>2,D,C,L|I,C|P,B|bq,Q,R|CE||E,O</td><td>83</td></tr>
<tr><td>Axsäter (2001b)</td><td>2,D,C,G|I,C|B,B|q,Q,N|C||AC,C</td><td>32</td></tr>
<tr><td>Axsäter (2003a)</td><td>2,D,C,G|I,C|B,B|q,Q,N|C||AC,O</td><td>94</td></tr>
<tr><td>Axsäter (2003b)</td><td>n,S,C,G|I,C|B,B|N,Q,N|CS||E,O</td><td>41</td></tr>
<tr><td>Axsäter (2005a)</td><td>2,D,C,G|I,C|G,B|q,Q,N|C||A,O</td><td>42</td></tr>
</table>

Reference	*Classification*	*Citations*
Axsäter (2005b)	n,C,C,G|I,G|G,B|N,F,N|C||A,O	56
Axsäter (2007)	2,D,C,G|I,C|BP,B|b,F,N|C||AC,C	13
Axsäter, Forsberg, et al. (1994)	2,D,C,G|I,C|B,B|bq,FQ,N|C||AC,O	29
Axsäter and Juntti (1996)	2,DS,C,G|I,C|P,B|Qq,Q,N|C||ES,C	72
Axsäter, Kleijn, et al. (2004)	2,D,C,G|I,C|P,B|b,F,A|C||AC,O	19
Axsäter and Marklund (2008)	2,D,C,G|I,C|P,B|Oq,Q,N|C||E,O	37
Axsäter, Marklund, and Silver (2002)	2,D,D,G|I,C|G,B|O,F,A|C||AS,O	65
Axsäter, Olsson, et al. (2007)	2,D,C,G|I,C|B,B|q,Q,N|C||AC,O	8
Axsäter and Rosling (1993)	n,C,C,G|I,G|G,B|Qq,Q,N|U||E,C	255
Axsäter and Rosling (1994)	n,G,D,G|I,C|G,B|BOQq,FQ,N|U||E,C	65
Axsäter and Rosling (1999)	n,CG,D,L|F,C|G,B|q,Q,N|U||E,C	24
Axsäter and Zhang (1996)	2,D,C,G|I,C|B,B|b,F,N|C||E,P	11
Axsäter and Zhang (1999)	2,D,C,G|I,C|P,B|q,Q,N|C||E,O	93
Badinelli (1992)	n,S,C,G|I,C|B,B|q,Q,N|CS||E,P	56
Badinelli and Schwarz (1988)	2,D,C,G|I,C|P,B|q,Q,N|C||AC,O	34
Banerjee, Burton, et al. (2003)	2,D,D,G|I,C|G,B|O,F,R|M||S,P	95
Banerjee, Banerjee, et al. (2001)	2,D,D,L|I,C|N,B|q,Q,N|M||S,P	51
Basten et al. (2015)	n,G,C,G|I,G|P,B|b,F,N|CS||AC,CO	20
Benjaafar and ElHafsi (2006)	2,C,C,G|F,E|P,L|N,F,N|C||E,O	181
Benjaafar, ElHafsi, et al. (2011)	n,C,C,G|F,E|P,BL|N,F,N|C||CE,O	33
Berling and Farvid (2014)	2,D,C,G|I,C|BG,B|q,Q,N|U||AC,FP	0
Berling and Marklund (2006)	2,D,C,G|I,C|N,B|q,Q,N|C||AC,O	20
Berling and Marklund (2013)	2,D,C,G|I,C|B,B|q,Q,N|CS||AC,O	12
Berling and Marklund (2014)	2,D,C,G|I,C|G,B|q,Q,N|CS||ACF,O	13
Berling and Martínez-de-Albéniz (2016a)	x,S,C,G|I,C|P,B|N,F,E|C||E,O	1
Berling and Martínez-de-Albéniz (2016b)	n,S,C,G|I,O|P,B|N,F,E|C||CE,O	1
Bertazzi et al. (2016)	2,D,D,G|BF,C|U,L|b,F,R|C||ACE,CO	1
Billington et al. (2004)	n,G,D,G|I,C|U,G|b,F,U|C||AF,O	70
Bollapragada, Kuppusamy, et al. (2015)	2,G,D,G|F,C|G,B|N,F,A|C||AC,O	3
Bollapragada, Akella, et al. (1998)	2,D,D,G|I,C|N,B|O,F,N|C||A,O	37
Bossert and Willems (2007)	n,G,D,G|I,C|U,G|b,F,U|C||AFS,O	33
Boulaksil (2016)	2,S,D,G|F,C|M,B|O,F,N|C||ACS,O	0
Braun et al. (2003)	n,G,D,G|F,C|G,B|O,F,N|C||S,O	169
Burton and Banerjee (2005)	2,D,D,G|I,C|G,B|b,F,R|M||CS,C	56
Buyukkurt and Parlar (1993)	2,D,C,G|F,E|P,B|b,F,A|M||ACS,C	20
Cachon (1999)	2,D,D,G|I,C|DU,B|q,Q,N|M||CE,O	291
Cachon (2001)	2,D,D,G|I,C|D,B|q,Q,N|C||ES,O	126
Cachon and Fisher (1997)	2,D,C,G|I,C|G,B|q,Q,N|CS||F,O	271
Cachon and Fisher (2000)	2,D,D,G|I,C|D,B|q,Q,N|C||AC,C	1933
Cachon and Zipkin (1999)	2,S,D,EL|I,C|G,B|Bb,F,N|CE||E,C	724
Caggiano, Jackson, et al. (2007)	n,D,C,G|I,C|P,B|b,F,N|CS||A,O	59
Caggiano, Muckstadt, et al. (2006)	2,D,D,G|F,C|D,B|N,F,E|C||AC,O	55
Cao and Silver (2005)	2,D,D,G|I,C|N,B|B,F,A|C||AC,O	13
Ceryan et al. (2012)	2,C,C,G|F,E|P,B|N,F,N|C||AC,O	20
Chao and Zhou (2007)	n,S,D,G|I,C|G,B|B,F,N|C||E,O	14
Chao and Zhou (2009)	n,S,D,G|I,C|G,B|N,Q,N|C||E,O	44
Chen (1998)	n,S,C,G|I,C|B,B|Qq,Q,N|C||E,CP	416
Chen (1999a)	2,DS,C,G|I,C|P,B|NO,F,N|C||AC,O	34
Chen (1999b)	n,S,D,G|I,C|G,B|N,F,N|C||CE,O	394
Chen (2000)	n,CS,D,G|I,C|G,B|N,Q,N|C||E,O	163
Chen, Drezner, et al. (2000)	2,S,D,L|I,C|G,B|b,F,N|U||CE,P	2108
Chen and Samroengraja (2000)	2,D,D,G|I,C|D,B|O,F,A|C||ACE,O	50
Chen and Song (2001)	n,S,D,G|I,C|M,B|N,F,N|C||E,O	177
Chen and Zheng (1994a)	n,S,CD,G|I,C|B,B|Q,Q,N|C||ES,P	131
Chen and Zheng (1994b)	23n,CDS,D,G|I,C|G,B|N,F,N|C||A,O	247
Chen and Zheng (1997)	2,D,C,G|I,C|B,B|Q,Q,N|C||ACE,C	161
Chen and Zheng (1998)	n,S,C,G|I,C|B,B|Q,Q,N|C||AE,O	77
Chen, Feng, et al. (2002)	2,D,D,G|I,C|G,B|q,Q,N|C||E,P	17
Chen and Li (2015)	n,S,C,G|I,C|PU,G|q,Q,U|CS||CE,O	9
Chen, Song, and Zhang (2016)	n,S,D,G|I,C|M,B|N,F,N|C||AC,FO	0

<table>
<tr><th>Reference</th><th>Classification</th><th>Citations</th></tr>
<tr><td>Chen and Muharremoglu (2014)</td><td>n,C,D,E|I,C|G,B|N,F,N|C||E,O</td><td>2</td></tr>
<tr><td>Chen and Cheng (2014)</td><td>n,S,D,E|I,C|F,B|B,F,N|C||E,O</td><td>3</td></tr>
<tr><td>Cheng, Ettl, et al. (2002)</td><td>n,G,D,G|I,G|N,B|b,F,N|C||AS,O</td><td>115</td></tr>
<tr><td>Cheng, Gao, et al. (2011)</td><td>2,C,C,G|F,E|P,L|N,F,N|C||ACE,O</td><td>17</td></tr>
<tr><td>Cheung and Hausman (2000)</td><td>2,D,C,G|I,C|R,B|q,Q,N|C||ACE,P</td><td>39</td></tr>
<tr><td>Cheung and Lee (2002)</td><td>2,D,C,G|I,C|P,B|Q,Q,R|C||E,C</td><td>262</td></tr>
<tr><td>Chew and Johnson (1995)</td><td>2,D,C,G|I,C|B,B|s,F,N|S||AS,P</td><td>4</td></tr>
<tr><td>Chew and Tang (1995)</td><td>2,D,C,G|I,C|P,B|s,F,N|C||AC,P</td><td>7</td></tr>
<tr><td>Chiang and Monahan (2005)</td><td>2,D,C,G|I,G|P,L|b,F,R|C||E,P</td><td>217</td></tr>
<tr><td>Clark and Scarf (1960)</td><td>n,DS,D,G|I,C|G,B|N,F,N|C||E,O</td><td>1883</td></tr>
<tr><td>Clark and Scarf (1962)</td><td>n,S,D,G|I,C|G,B|N,F,N|C||A,O</td><td>123</td></tr>
<tr><td>Cobb (2016)</td><td>2,S,C,G|I,G|N,L|q,Q,N|C||CE,O</td><td>1</td></tr>
<tr><td>Cohen, Kleindorfer, et al. (1986)</td><td>n,D,C,G|I,C|G,B|b,F,ER|CS||AC,O</td><td>152</td></tr>
<tr><td>Cohen and Lee (1988)</td><td>n,G,C,G|I,C|G,B|q,Q,E|C||A,O</td><td>834</td></tr>
<tr><td>Cohen, Kamesam, et al. (1990)</td><td>n,D,D,G|I,C|GU,G|s,F,ER|CS||F,O</td><td>192</td></tr>
<tr><td>Dada (1992)</td><td>2,D,C,G|I,G|P,B|b,F,OR|C||A,P</td><td>107</td></tr>
<tr><td>Dayanik et al. (2003)</td><td>2,G,C,G|F,G|P,BL|b,F,N|S||A,P</td><td>51</td></tr>
<tr><td>de Bodt and Graves (1985)</td><td>n,S,C,G|I,C|G,B|Q,Q,N|C||A,O</td><td>152</td></tr>
<tr><td>de Kok (1990)</td><td>2,D,D,G|I,C|G,B|B,F,A|S||A,P</td><td>77</td></tr>
<tr><td>de Kok et al. (2005b)</td><td>n,G,D,G|I,C|G,B|B,F,N|M||F,O</td><td>100</td></tr>
<tr><td>de Kok and Visschers (1999)</td><td>n,G,D,G|I,C|G,B|B,F,N|C||C,F</td><td>57</td></tr>
<tr><td>DeCroix (2006)</td><td>n,S,D,G|I,C|G,B|N,F,N|C||E,O</td><td>110</td></tr>
<tr><td>DeCroix, Song, et al. (2009)</td><td>2,G,C,G|I,C|P,B|b,F,N|C||ACE,O</td><td>29</td></tr>
<tr><td>DeCroix and Zipkin (2005)</td><td>n,C,D,G|I,C|G,B|N,F,N|C||ACE,O</td><td>100</td></tr>
<tr><td>Dekker et al. (1998)</td><td>2,D,D,G|I,C|G,B|O,F,R|C||A,O</td><td>14</td></tr>
<tr><td>Demirel et al. (2015)</td><td>2,S,D,G|F,C|G,L|b,F,N|C||CE,O</td><td>1</td></tr>
<tr><td>Deuermeyer and Schwarz (1981)</td><td>2,D,C,G|I,C|P,B|q,Q,N|U||AC,P</td><td>249</td></tr>
<tr><td>Diaz and Fu (1997)</td><td>n,D,C,G|F,G|P,B|b,F,N|S||AC,P</td><td>177</td></tr>
<tr><td>Diks and de Kok (1996)</td><td>2,D,D,G|I,C|G,B|B,F,AR|S||AC,O</td><td>89</td></tr>
<tr><td>Diks and de Kok (1998)</td><td>n,D,D,G|I,C|G,B|N,F,N|C||E,O</td><td>135</td></tr>
<tr><td>Diks and de Kok (1999)</td><td>n,D,D,G|I,C|G,B|B,F,N|C||AC,O</td><td>71</td></tr>
<tr><td>Doğru et al. (2010)</td><td>2,G,C,G|I,C|B,B|b,F,A|C||AC,O</td><td>54</td></tr>
<tr><td>Doğru et al. (2016)</td><td>2,G,C,G|I,C|B,B|N,F,A|C||AC,O</td><td>2</td></tr>
<tr><td>Doğru, de Kok, et al. (2009)</td><td>2,D,D,G|I,C|D,B|N,F,N|C||CE,O</td><td>14</td></tr>
<tr><td>Doğru and Özen (2015)</td><td>2,D,C,L|I,C|P,B|b,F,N|CS||AF,O</td><td>1</td></tr>
<tr><td>Dong and Lee (2003)</td><td>n,S,D,G|I,C|G,B|N,F,N|C||AE,O</td><td>107</td></tr>
<tr><td>Egri (2012)</td><td>n,S,C,G|I,C|NU,G|b,F,U|CS||ES,O</td><td>6</td></tr>
<tr><td>Ekanayake et al. (2016)</td><td>2,D,D,G|I,C|P,L|s,F,O|M||COS,CP</td><td>0</td></tr>
<tr><td>ElHafsi (2009)</td><td>2,C,C,G|F,E|B,L|N,F,N|C||AE,O</td><td>63</td></tr>
<tr><td>ElHafsi, Camus, et al. (2008)</td><td>2,G,C,G|F,E|P,L|N,F,N|C||ACE,O</td><td>23</td></tr>
<tr><td>ElHafsi and Hamouda (2015)</td><td>2,C,C,G|F,E|P,B|N,F,N|C||ACE,O</td><td>5</td></tr>
<tr><td>ElHafsi, Zhi, et al. (2015)</td><td>2,C,C,G|F,E|P,L|N,F,A|C||ACE,O</td><td>8</td></tr>
<tr><td>Eppen and Schrage (1981)</td><td>2,D,D,G|I,C|N,B|B,F,N|C||E,O</td><td>497</td></tr>
<tr><td>Erkip et al. (1990)</td><td>2,D,D,G|I,C|G,B|B,F,N|C||E,O</td><td>224</td></tr>
<tr><td>Ernst and Pyke (1992)</td><td>2,C,D,G|I,C|G,B|q,Q,N|CS||AC,O</td><td>16</td></tr>
<tr><td>Eruguz et al. (2013)</td><td>n,S,D,G|I,C|N,L|b,F,U|S||S,O</td><td>5</td></tr>
<tr><td>Eruguz et al. (2014)</td><td>n,G,D,G|I,C|U,G|b,F,U|C||ACE,O</td><td>14</td></tr>
<tr><td>Ettl et al. (2000)</td><td>n,G,D,G|I,G|G,B|b,F,N|CS||AS,O</td><td>326</td></tr>
<tr><td>Farasyn et al. (2011)</td><td>n,G,D,G|I,C|N,B|S,F,U|C||F,O</td><td>42</td></tr>
<tr><td>Fattahi et al. (2015)</td><td>2,S,D,GL|F,C|G,L|s,F,N|C||ACS,O</td><td>13</td></tr>
<tr><td>Federgruen and Zipkin (1984a)</td><td>2,D,D,G|I,C|N,B|O,F,N|C||,O</td><td>130</td></tr>
<tr><td>Federgruen and Zipkin (1984b)</td><td>2,D,D,G|I,C|G,B|O,F,N|C||A,O</td><td>169</td></tr>
<tr><td>Federgruen and Zipkin (1984c)</td><td>2,DS,D,G|I,C|GN,B|O,F,N|C||E,O</td><td>360</td></tr>
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<tr><td>Forsberg (1995)</td><td>2,D,C,G|I,C|B,B|b,F,N|C||,O</td><td>76</td></tr>
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<tr><td>Iravani et al. (2003)</td><td>2,G,C,G|I,E|P,BL|b,F,R|M||CE,O</td><td>34</td></tr>
<tr><td>Jackson (1988)</td><td>2,D,D,G|I,C|NP,B|O,F,N|C||A,O</td><td>180</td></tr>
<tr><td>Jackson and Muckstadt (1989)</td><td>2,D,D,G|I,C|G,B|O,F,A|C||A,O</td><td>2</td></tr>
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<tr><td>Jönsson and Silver (1987a)</td><td>2,D,D,G|I,C|N,B|O,F,R|C||A,O</td><td>214</td></tr>
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<tr><td>Klosterhalfen, Dittmar, et al. (2013)</td><td>n,S,D,G|I,C|G,B|b,F,E|C||AC,O</td><td>16</td></tr>
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<tr><td>Ko et al. (2011)</td><td>2,C,C,G|F,E|P,B|b,F,N|U||AC,F</td><td>5</td></tr>
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<tr><td>Lagodimos and Anderson (1993)</td><td>n,D,D,G|I,C|G,B|O,F,N|S||ACS,P</td><td>49</td></tr>
<tr><td>Lagodimos, de Kok, et al. (1995)</td><td>2,S,D,G|I,C|N,B|B,F,N|S||CE,P</td><td>15</td></tr>
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<tr><td>Lee and Zipkin (1995)</td><td>n,D,C,G|F,E|P,B|b,F,N|M||AC,P</td><td>28</td></tr>
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<tr><td>McGavin et al. (1993)</td><td>2,D,D,G|I,C|G,L|O,F,N|C||AS,C</td><td>120</td></tr>
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<tr><td>Mitra and Chatterjee (2004b)</td><td>2,D,D,G|I,C|N,B|b,F,O|C||AC,P</td><td>31</td></tr>
<tr><td>Moinzadeh (2002)</td><td>2,D,C,G|I,C|P,B|O,Q,N|C||E,C</td><td>256</td></tr>
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Reference	*Classification*	*Citations*
Molinder (1997)	n,CG,D,G|I,G|D,B|O,F,N|CS||S,O	111
Moncayo-Martinez, Ramirez–Lopez, et al. (2016)	n,C,D,G|I,C|U,G|b,F,N|C||A,O	3
Moncayo-Martinez, Resendiz-Flores, et al. (2014)	n,G,D,G|I,C|UU,G|b,F,U|C||EF,O	4
Muckstadt (1973)	2,G,C,G|I,G|B,B|b,F,N|C||A,O	488
Muckstadt and Thomas (1980)	2,D,C,G|I,C|P,B|b,F,N|CS||AF,O	172
Muharremoglu and Tsitsiklis (2008)	n,S,D,G|I,G|M,B|N,F,N|C||,O	92
Muharremoglu and Yang (2010)	n,S,D,G|I,G|G,B|b,F,N|C||E,P	20
Nadar et al. (2014)	2,G,C,G|I,E|P,L|N,F,A|C||E,O	18
Nadar et al. (2016)	2,G,C,G|I,E|P,L|N,Q,A|C||AC,O	3
Nahmias and Smith (1994)	2,D,D,G|I,C|G,BL|O,F,N|C||E,O	163
Neale and Willems (2009)	n,G,D,G|I,C|NU,G|b,F,U|C||A,O	39
Needham and Evers (1998)	2,D,D,G|I,G|G,L|q,Q,ER|C||ACS,C	62
Nepal et al. (2011)	n,G,D,G|I,C|NU,G|b,F,U|M||E,O	18
Ni and Shu (2015)	n,G,D,G|I,C|U,G|b,F,U|C||CE,O	4
Nozick and Turnquist (2001)	2,D,C,G|I,C|GP,B|b,F,N|C||E,O	168
Oh et al. (2014)	2,G,D,G|I,C|G,B|N,F,A|C||ACE,O	8
Ohno et al. (2016)	3n,S,D,G|F,C|U,BL|N,O,N|C||AC,O	3
Özer (2003)	2,D,D,G|I,C|D,B|O,F,N|C||ACE,O	129
Özkan et al. (2015a)	2,D,C,G|I,C|P,B|b,F,R|C||AC,O	10
Özkan et al. (2015b)	2,D,C,G|I,C|P,B|b,F,ER|C||AC,P	10
Parker and Kapuscinski (2004)	2,S,D,G|F,C|G,B|N,F,N|C||E,O	84
Patriarca et al. (2016)	2,D,C,G|I,G|P,B|b,F,R|C||ACF,O	0
Perlman et al. (2001)	2,D,C,G|F,G|B,B|b,F,E|C||CE,C	42
Petrovic et al. (1998)	n,S,D,G|I,C|F,B|b,F,N|CS||CS,O	366
Petrovic et al. (1999)	n,S,D,G|I,C|F,B|b,F,N|CS||CS,O	379
Plambeck (2008)	2,G,C,G|F,C|R,L|O,F,E|C||ACE,O	23
Plambeck and Ward (2006)	2,G,C,G|F,O|R,B|N,F,A|C||E,O	65
Plambeck and Ward (2007)	2,G,C,G|F,C|R,L|N,F,E|C||E,O	36
Pyke (1990)	2,D,C,G|I,E|G,B|b,F,R|C||S,C	72
Raghunathan (2001)	2,S,D,L|I,C|M,B|b,F,N|C||AC,C	370
Rambau and Schade (2010)	n,D,D,G|I,G|D,G|b,F,EO|C||AC,O	8
Rambau and Schade (2014)	n,D,D,G|I,G|D,L|s,F,EO|C||ACS,CO	2
Rappold and Muckstadt (2000)	2,D,D,G|F,C|G,B|B,F,N|C||AC,O	31
Rappold and van Roo (2009)	2,D,C,G|F,E|P,B|b,F,N|C||AC,O	60
Reiman et al. (2016a)	2,G,C,G|I,C|B,B|O,F,A|C||E,F	1
Reiman et al. (2016b)	2,G,C,G|I,C|B,B|b,F,N|C||E,O	1
Reiman and Wang (2012)	2,G,C,G|I,C|B,B|b,F,A|C||E,O	21
Reiman and Wang (2015)	2,G,C,G|I,C|B,B|b,F,A|C||A,O	14
Rong et al. (2014)	n,D,C,G|I,C|P,B|b,F,N|C||AC,O	3
Rosenbaum (1981)	2,D,C,G|I,G|N,B|O,O,N|S||AC,O	48
Rosling (1989)	n,C,D,G|I,C|G,B|N,F,N|C||E,O	329
Routroy and Kodali (2005)	3,S,C,G|I,C|N,L|q,Q,N|C||A,O	35
Roy and Raghavan (2014)	2,D,D,E|I,C|N,B|B,F,A|E||A,O	1
Salzarulo and Jacobs (2014)	2,S,C,GL|F,C|P,B|s,F,N|C||AC,O	11
Santos and Bispo (2016)	n,G,D,G|F,C|G,B|B,F,N|C||ACS,O	0
Schildbach and Morari (2016)	n,G,D,G|BF,CG|G,B|O,F,R|CS||AC,O	10
Schmidt and Nahmias (1985)	2,C,D,G|I,C|G,B|N,F,N|C||E,O	139
Schneider et al. (1995)	2,D,D,G|I,C|G,B|s,F,N|CS||AC,O	28
Schoenmeyr and Graves (2009)	n,CS,D,G|I,C|GU,G|b,F,U|C||EF,O	41
Schultz (1983)	2,D,D,G|I,C|G,B|s,F,N|C||E,F	10
Schwarz (1989)	2,D,D,G|I,C|N,B|b,F,A|C||CE,P	135
Schwarz et al. (1985)	2,D,C,G|I,C|P,B|q,Q,N|C||A,O	114
Seferlis and Giannelos (2004)	n,G,D,G|F,C|G,BL|N,F,N|C||AC,O	111
Seifbarghy and Jokar (2006)	2,D,C,G|I,C|P,L|q,Q,N|C||AC,O	57
Seo et al. (2002)	2,D,C,G|I,C|P,B|q,Q,E|C||AC,O	41
Shang (2008)	n,S,C,G|I,C|R,B|Q,F,N|C||AC,O	30
Shang (2012)	n,S,D,G|I,C|G,B|B,F,N|C||AC,O	14
Shang and Song (2003)	n,S,C,G|I,C|B,B|B,F,N|C||AC,O	138
Shang and Song (2006)	n,S,C,G|I,C|P,B|B,F,N|C||AC,FO	23
Shang and Song (2007)	n,S,C,G|I,C|B,B|BQ,FQ,N|C||AC,O	17

<table>
<tr><th>Reference</th><th>Classification</th><th>Citations</th></tr>
<tr><td>Shang, Song, and Zipkin (2009)</td><td>n,S,D,G|I,C|G,B|q,Q,N|C||E,O</td><td>35</td></tr>
<tr><td>Shang, Tao, et al. (2015)</td><td>n,D,D,G|I,C|P,B|B,F,N|C||AC,O</td><td>7</td></tr>
<tr><td>Shang and Zhou (2009)</td><td>n,S,D,G|I,C|G,B|Q,F,N|C||AC,O</td><td>13</td></tr>
<tr><td>Shang and Zhou (2010)</td><td>n,S,D,G|I,C|D,B|Q,Q,N|C||AC,O</td><td>45</td></tr>
<tr><td>Shang, Zhou, and van Houtum (2010)</td><td>n,S,D,G|I,C|G,B|O,F,N|C||CE,O</td><td>19</td></tr>
<tr><td>Sherbrooke (1968)</td><td>2,D,C,G|I,G|B,B|b,F,N|C||A,O</td><td>1222</td></tr>
<tr><td>Sherbrooke (1986)</td><td>3,D,C,G|I,C|P,B|b,F,N|C||A,P</td><td>303</td></tr>
<tr><td>Sherbrooke (1992)</td><td>2,D,C,G|I,G|P,B|b,F,R|C||AC,O</td><td>125</td></tr>
<tr><td>Shi and Zhao (2014)</td><td>2,G,C,G|I,C|G,B|b,F,A|C||CE,C</td><td>1</td></tr>
<tr><td>Shu and Karimi (2009)</td><td>n,G,D,G|I,C|GU,G|b,F,U|C||AC,O</td><td>22</td></tr>
<tr><td>Simchi-Levi and Zhao (2003)</td><td>2,S,D,G|F,C|D,B|O,F,N|C||ACE,O</td><td>111</td></tr>
<tr><td>Simon (1971)</td><td>2,D,C,G|I,C|P,B|b,F,N|C||E,F</td><td>158</td></tr>
<tr><td>Simpson (1958)</td><td>n,S,C,G|I,C|U,G|b,F,U|C||E,O</td><td>199</td></tr>
<tr><td>Simpson (1978)</td><td>2,S,D,G|I,C|G,B|N,F,O|C||E,O</td><td>210</td></tr>
<tr><td>Sinha and Krishnamurthy (2016)</td><td>2,C,C,G|F,C|P,B|O,F,R|C||ACE,COP</td><td>0</td></tr>
<tr><td>Sitompul et al. (2008)</td><td>n,S,D,G|F,C|NU,G|b,F,U|C||AC,O</td><td>55</td></tr>
<tr><td>Slay (1984)</td><td>3,D,C,G|I,CE|P,B|b,F,N|S||A,O</td><td>134</td></tr>
<tr><td>Sleptchenko et al. (2002)</td><td>n,D,C,G|F,G|P,B|b,F,N|C||AC,O</td><td>126</td></tr>
<tr><td>Song (1998)</td><td>2,G,C,G|I,C|R,B|b,F,N|E||E,P</td><td>169</td></tr>
<tr><td>Song (2000)</td><td>2,G,C,G|I,C|BP,B|q,Q,N|S||E,P</td><td>54</td></tr>
<tr><td>Song, Xu, et al. (1999)</td><td>2,C,C,G|F,E|P,BL|b,F,N|S||E,P</td><td>199</td></tr>
<tr><td>Song and Zhao (2009)</td><td>2,G,C,G|I,C|P,B|b,F,N|C||AC,O</td><td>45</td></tr>
<tr><td>Stenius et al. (2016)</td><td>2,D,C,G|I,CG|B,B|bq,FQ,N|C||E,O</td><td>4</td></tr>
<tr><td>Svoronos and Zipkin (1988)</td><td>2,D,C,G|I,C|P,B|q,Q,N|C||AC,P</td><td>251</td></tr>
<tr><td>Svoronos and Zipkin (1991)</td><td>n,D,C,G|I,G|P,B|b,F,N|C||AC,P</td><td>234</td></tr>
<tr><td>Tee and Rossetti (2002)</td><td>2,D,C,G|I,C|P,B|q,Q,N|M||CS,P</td><td>68</td></tr>
<tr><td>Tempelmeier (1993)</td><td>2,D,D,G|I,G|G,B|q,Q,N|C||AC,O</td><td>23</td></tr>
<tr><td>Tian et al. (2011)</td><td>n,G,D,G|F,C|NU,G|b,F,U|C||A,O</td><td>36</td></tr>
<tr><td>Topan et al. (2010)</td><td>2,D,C,G|I,C|P,B|O,Q,N|C||CE,O</td><td>31</td></tr>
<tr><td>van den Berg et al. (2016)</td><td>2,D,C,G|I,CE|P,L|q,Q,OR|CS||ACF,O</td><td>2</td></tr>
<tr><td>van der Heijden (1992)</td><td>2n,D,C,G|I,G|B,B|b,F,N|C||A,P</td><td>12</td></tr>
<tr><td>van der Heijden (1997)</td><td>2,D,D,G|I,C|G,B|B,F,N|S||,P</td><td>46</td></tr>
<tr><td>van der Heijden (1999)</td><td>2,D,D,G|I,C|G,B|b,F,N|S||AC,O</td><td>42</td></tr>
<tr><td>van der Heijden (2000)</td><td>n,D,D,G|I,C|G,B|B,F,N|CS||AC,O</td><td>31</td></tr>
<tr><td>van der Heijden et al. (1997)</td><td>n,D,D,G|I,C|G,B|B,F,N|S||AS,C</td><td>82</td></tr>
<tr><td>van der Heijden et al. (1999)</td><td>n,D,D,G|I,G|G,B|B,F,N|S||,O</td><td>22</td></tr>
<tr><td>van Donselaar (1990)</td><td>2,D,D,G|I,C|G,B|B,F,N|S||E,P</td><td>46</td></tr>
<tr><td>van Donselaar and Wijngaard (1987)</td><td>2,D,D,G|I,C|G,B|B,F,N|CS||A,P</td><td>47</td></tr>
<tr><td>van Houtum, Scheller-Wolf, et al. (2007)</td><td>n,S,D,G|I,C|G,B|N,F,N|C||E,O</td><td>50</td></tr>
<tr><td>van Houtum and Zijm (1991)</td><td>n,C,D,G|I,C|G,B|N,F,N|CS||E,O</td><td>84</td></tr>
<tr><td>van Jaarsveld and Scheller-Wolf (2015)</td><td>2,G,C,G|I,C|P,B|b,F,A|C||ACES,O</td><td>12</td></tr>
<tr><td>van Wijk et al. (2013)</td><td>2,D,C,G|I,E|P,B|b,F,R|C||E,O</td><td>8</td></tr>
<tr><td>Veatch and Wein (1994)</td><td>2,S,C,G|F,E|P,B|N,F,N|C||CE,O</td><td>142</td></tr>
<tr><td>Verrijdt and de Kok (1995)</td><td>n,D,D,G|I,C|G,B|B,F,N|S||AC,P</td><td>68</td></tr>
<tr><td>Verrijdt and de Kok (1996)</td><td>2,D,D,G|I,C|G,B|B,F,N|S||AC,P</td><td>64</td></tr>
<tr><td>Wang and Axsäter (2013)</td><td>2,D,C,G|I,C|P,B|O,O,N|C||CE,O</td><td>8</td></tr>
<tr><td>Wang, Cohen, et al. (2000)</td><td>2,D,C,G|I,G|P,B|b,F,N|M||AC,P</td><td>66</td></tr>
<tr><td>Wheatley et al. (2015)</td><td>2,D,C,G|I,C|P,B|b,F,N|CS||C,O</td><td>17</td></tr>
<tr><td>Wieland et al. (2012)</td><td>n,G,D,G|I,C|U,G|b,F,U|C||E,O</td><td>15</td></tr>
<tr><td>Woerner et al. (2016)</td><td>n,C,D,G|F,CG|G,B|b,F,N|C||ACS,O</td><td>0</td></tr>
<tr><td>Wong, Cattrysse, et al. (2005)</td><td>2,D,C,G|I,E|P,B|b,F,R|C||AC,O</td><td>93</td></tr>
<tr><td>Wong, Kranenburg, et al. (2007)</td><td>2,D,C,G|I,G|P,B|b,F,N|CS||ACE,O</td><td>48</td></tr>
<tr><td>Xiang and Rossetti (2014)</td><td>2,D,C,G|I,CE|P,B|q,Q,N|M||ACS,C</td><td>0</td></tr>
<tr><td>Xu et al. (2016)</td><td>n,C,C,G|I,G|G,B|N,F,N|C||CE,O</td><td>4</td></tr>
<tr><td>Yang et al. (2013)</td><td>2,D,C,G|I,C|P,B|b,F,R|CS||ACF,P</td><td>17</td></tr>
<tr><td>Ye and You (2016)</td><td>n,G,D,G|F,G|G,B|b,F,R|C||CS,O</td><td>6</td></tr>
<tr><td>Yoo et al. (1997)</td><td>2,D,D,G|I,C|G,B|q,Q,N|C||C,O</td><td>21</td></tr>
<tr><td>Yoon et al. (2015)</td><td>2,D,C,G|F,E|P,B|b,F,N|C||ACS,FP</td><td>0</td></tr>
<tr><td>You and Grossmann (2011)</td><td>n,G,D,G|F,C|NU,G|O,F,U|C||CE,O</td><td>71</td></tr>
<tr><td>Zanjani and Nourelfath (2014)</td><td>2,G,D,G|F,G|D,B|O,F,N|C||AC,O</td><td>10</td></tr>
</table>

Reference	*Classification*	*Citations*
Zhang (1997)	2,G,D,G|I,C|N,B|b,F,N|CS||CE,O	87
Zijm and van Houtum (1994)	n,C,D,G|FI,C|G,B|B,F,N|C||E,C	25
Zipkin (1984)	2,D,D,G|I,C|N,B|B,F,N|C||AC,P	75
Zipkin (1991)	n,D,C,G|I,G|B,B|b,F,N|S||ACE,P	29

Table 3: Classification string and number of citations (as of July 2017)