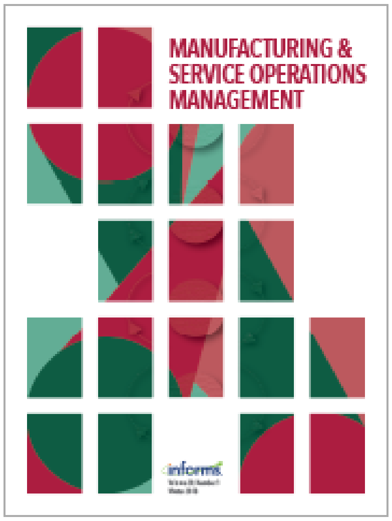

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20th Anniversary Invited Article

Capacity and Inventory Management: Review, Trends, and Projections

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Abstract. We present a reproducible, objective review of research trends using text mining and citations of papers published in *Manufacturing & Service Operations Management* during its first 20 years whose abstracts or keywords contain capacity or inventory. The review is followed by our subjective projections on future research opportunities.

History: This paper has been accepted for the *Manufacturing & Service Operations Management* 20th Anniversary Special Issue.

Keywords: capacity • inventory • stock • research review • research trends • text mining

1. Introduction

Capacity and inventory management are fundamental topics of operations management, as they concern the planning and control of the supply or processing side of matching supply and demand. As such, they constitute two active research areas in the operations management field that, as we will show, are fast evolving. This evolution coincides with, or slightly lags, the changes in the forces enabling the supply side: production, transportation, and information technologies as well as the openness of the global sourcing opportunities. Considering these advancements, capacity and inventory research is increasingly addressing new challenges in this dynamic environment.

In this paper, we first review the basic questions and connections of inventory and capacity management; see Section 2. We then present the statistics and key features of the publications in these two areas in *Manufacturing & Service Operations Management* (*M&SOM*) in the past 20 years, followed by a discussion of how these features reflect technological developments and industry dynamics, with references to some representative articles; see Section 3. Guided by the past evolution, we present our projections on potentially important future research directions in Section 4, before we conclude in Section 5.

An important preparatory step for this paper involved selecting all capacity and inventory papers published in *M&SOM* in the past 20 years. We created a spreadsheet with all papers and the following attributes per paper: title, authors, addresses, abstract, keywords, year of publication, and number of citations in Google Scholar (per January 16, 2019). We then performed text mining (using R) to identify all capacity and inventory papers. A paper was classified as an inventory paper if its abstract or keywords contained the stems "inventor" or "stock" (notice that inventory and inventories are covered by "inventor"). Similarly, a paper was classified as a capacity paper if its abstract or keywords contained the stem "capacit" (which covers capacity, capacities, and capacitated). Table 1 summarizes the results: of all 655 papers published in the years 1999–2018, 218 and 147 papers are part of the inventory and capacity domains, respectively. Of these papers, 46 papers are part of both, and hence we have $218 + 147 - 46 = 318$ papers that belong to the capacity–inventory domain. These 318 papers constitute 49% of all papers. Table 1 also presents the numbers per five-year period, or "lustrum," and shows that the capacity–inventory share decreased somewhat in the last lustrum.

We acknowledge that text timing is a crude and imperfect method to select papers, but it has the advantage of being reproducible, objective, and able to mine big data fast at low cost. We also found it to be "good enough" for our purposes: the selection using automated text mining matched for roughly 80% with a selection based on our own reading of titles and abstracts. We established this 80% estimate by comparing both methods for a subset of 75 papers in which we identified 13 false negatives and no false positives. This accuracy is sufficient to show some interesting statistics and trends for the capacity–inventory research area in Section 3. The drawbacks of a manual,

Table 1. Defining Our "Domain" of Capacity or Inventory *M&SOM* Papers Using Text Mining per Lustrum

Number of published in *M&SOM*	1999–2003	2004–2008	2009–2013	2014–2018	Total	Percentage
Papers	101	140	207	207	655	100%
Abstracts *or* keywords containing word stems:						
Inventor *or* stock	46	54	59	58	217	33%
Capacit	25	25	56	41	147	22%
(Inventor *or* stock) *and* capacit	12	11	6	17	46	7%
Capacity–inventory papers, our study domain	59	68	109	82	318	49%
As a fraction of all papers	58%	49%	53%	40%	49%	

subjective selection based on own reading would have been high cost (very time-consuming) and lack of reproducibility. The three of us had different opinions on whether several papers belonged to the capacity–inventory research area. A key reason is that capacity or inventory plays a role in multiple papers, yet only a minor role (5%–10% of all papers). For example, Aviv and Pazgal (2008) study the pricing of seasonal products for given initial inventory levels, and Corbett and Klassen (2006) focus on environmental issues within total quality management and supply chain management.

After we selected the papers belonging to our study domain, we performed a first analysis to estimate the impact of capacity and inventory papers by comparing their Google Scholar citations with the citations of all *M&SOM* papers. Given that absolute citations bias older papers, we also ranked paper impact on the basis of annual citation rate since publication year. (The latter appears to be a more predictive metric for young papers.) Table 2 presents the corresponding citation distributions by decile. We see only small differences when we compare the whole set of papers and the capacity–inventory papers. (We also looked at the 11 papers that won the *M&SOM* Best Paper Award, and we found that 9 of them belong to the capacity–inventory domain.) Table 3 lists the 10 papers with the highest citation scores: the first two columns concern all *M&SOM* papers, whereas the last two columns focus on our domain of capacity–inventory papers. Multiple papers with high absolute citations (first and third columns) also have high annual citation rates (second and forth columns). The second and forth columns also contain multiple recent papers, in agreement with citation rates being a more predictive metric for young papers. We also checked the selection accuracy of our text mining for the 22 different papers in Table 3: we identified three false negatives (Tsay and Agrawal 2000, Lariviere and Porteus 2001, Barnes-Schuster et al. 2002) and one false positive (Boudreau et al. 2003). This limited sample accuracy agrees with "roughly 80%."

Notice that our statistics derived from text mining do not differentiate between product and service operations. Indeed, Gans et al. (2003) is the most cited *M&SOM* paper, and, given that it concerns call centers where capacity is important, it is part of our domain. In the ensuing sections, however, we focus on *product supply activities*.

2. Basic Questions of Capacity and Inventory Management

2.1. Role of Capacity Management

All products need to be produced and then delivered to customers. The activities comprised by those production and transportation processes require the classical two assets: capital (money, property, plant, equipment, trucks, etc.) and labor (humans). Each asset type has finite capacity and requires time to perform the work. Central questions of capacity management are how to choose capacity levels and how to best exploit the existing capacity to maximize created value, which can be a function of the product quality and the customer response time. Deciding capacity levels

Table 2. The Distribution of Google Scholar Citations (as of January 16, 2019; Absolute and Citations per Year Since Publication Year) of Capacity or Inventory Papers Is Close to That of All *M&SOM* Papers

	Decile										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Citations (all *M&SOM* papers)	0	5	12	18	27	37	51	70	102	158	1529
Citations (capacity–inventory papers)	0	6	13	21	30	40	55	76	108	168	1529
Citations per year (all *M&SOM* papers)	0	1.4	2.3	3.1	4.0	4.8	6.3	8.0	10.5	15.9	95.6
Citations per year (capacity–inventory papers)	0	1.3	2.3	3.2	4.0	5.0	6.1	7.6	10.9	15.7	95.6

Table 3. The Top 10 Most Cited Papers (Google Scholar on January 16, 2019) in Decreasing Order of All *M&SOM* vs. Our Domain Papers

Rank	TopCited_All *M&SOM*	TopCited/Year_All *M&SOM*	TopCited_CapInvPapers	TopCited/Year_CapInvPapers
1	Gans et al. (2003)	Gans et al. (2003)	Gans et al. (2003)	Gans et al. (2003)
2	Lariviere and Porteus (2001)	Taylor (2018)	Bitran and Caldentey (2003)	Cachon et al. (2017)
3	Bitran and Caldentey (2003)	Lariviere and Porteus (2001)	Aviv and Pazgal (2008)	Bitran and Caldentey (2003)
4	Barnes-Schuster et al. (2002)	Cachon et al. (2017)	Tsay and Lovejoy (1999)	Aviv and Pazgal (2008)
5	Tsay and Agrawal (2000)	Bitran and Caldentey (2003)	Van Mieghem (2003)	Corbett and Klassen (2006)
6	Aviv and Pazgal (2008)	Aviv and Pazgal (2008)	Corbett and Klassen (2006)	Alan and Gaur (2018)
7	Garnett et al. (2002)	Barnes-Schuster et al. (2002)	Agrawal and Seshadri (2000)	Van Mieghem (2003)
8	Guide et al. (2003)	Ferreira et al. (2016)	Graves (1999)	Su (2008)
9	Tsay and Lovejoy (1999)	Corbett and Klassen (2006)	Graves and Willems (2000)	Bolton and Katok (2008)
10	Van Mieghem (2003)	Alan and Gaur (2018)	Boudreau et al. (2003)	Liu et al. (2010)

Note. CapInvPapers, capacity–inventory papers.

typically involves a more strategic-level investment problem, whereas exploiting existing capacity is considered at the tactical and operational planning levels.

2.2. Role of Inventory Management

To improve capacity utilization and customer response time, companies can produce in advance of actual demand and hold product in inventory (make to stock). Finished goods inventory then serves as a substitute of production capacity and can be considered stored production capacity, similar to energy stored in batteries. In contrast, input inventories (of raw material, components, or subassemblies) aim to prevent production idleness and therefore are complements of production capacity, as they enhance effective capacity. Inventory and capacity can thus be either substitutes or complements, depending on where inventory sits relative to capacity along the supply chain.

Inventory occupies space and ties up capital. The distribution of parts and final products often involves a network of central and regional distribution centers and retail stores. Therefore, inventory planning is essential to minimize the total inventory ordering, holding, and shortage costs. Classic topics include single-stage or multistage (multiechelon) inventory planning and static or dynamic optimal inventory control.

2.3. Interaction Between Capacity and Inventory Management

Even though inventory and capacity are connected, many research studies focus on one topic at a time. Among all papers published in *M&SOM*, Table 1 shows that 33% mention only inventory and 22% mention only capacity, whereas just 7% mention both. There is a good reason for this. A production or transportation stage is often part of the supply chains of multiple products, those supply chains have also other production/transportation stages, these stages are also part of other products, and so on. Hence, studying capacity and inventory in an integrated way quickly leads to very complex problems for large supply networks. In practice, it is common that the production and transportation stages promise fixed lead times and that inventory managers decide on the safety stocks within their supply chains based on these lead times. Nevertheless, relevant problems with a joint consideration of inventory and capacity have been studied as well. Theoretical insights have been obtained for, for example, a (bottleneck) production stage that produces multiple products to stock and supply chains for a single product with dedicated capacities for that product. For more complex problems, we see studies on, for example, advanced mixed integer problem formulations for the joint optimization of inventories and capacity allocations and the effect of more advanced/flexible interaction mechanisms than fixed lead times.

For the 7% of papers that mention both capacity and inventory in their abstracts or keywords, we list the top 10 most cited papers in Table 4. That table also presents the top 10 papers that mention capacity (inventory) but not inventory (capacity).

3. Review and Publication Trends in *M&SOM* Volumes 1–20 (1999–2018)

The past 20 years have been marked by rapid technological development, such as the internet, GPS, radio-frequency identification, smart phones, automation (robots and drones), big data, and artificial intelligence (AI). We have also experienced unprecedented levels of collaboration and globalization. As companies have located or outsourced their operations to take advantage of cheap and skilled labor, factory capacity, design and engineering expertise, and proximity to critical material and components, supply chains have become increasingly decentralized and spread out around the globe. Consequently, new issues and challenges have emerged, and the research community has responded with new theory and tools to understand and guide practice.

To investigate how specific topics have been studied in the capacity–inventory papers published

Table 4. The Top 10 Most Cited Domain Papers That Mention Capacity (but Not Inventory), Capacity and Inventory, or Inventory (but Not Capacity)

Rank	Capacity (no inventory)	Capacity *and* Inventory	Inventory (no Capacity)
1	Gans et al. (2003)	Van Mieghem (2003)	Aviv and Pazgal (2008)
2	Bitran and Caldentey (2003)	Anupindi et al. (2001)	Tsay and Lovejoy (1999)
3	Maglaras and Meissner (2006)	Van Mieghem and Rudi (2002)	Corbett and Klassen (2006)
4	So (2000)	Hall and Porteus (2000)	Agrawal and Seshadri (2000)
5	Liu et al. (2010)	Chand et al. (2002)	Graves (1999)
6	Wang et al. (2010)	Caldentey and Wein (2003)	Graves and Willems (2000)
7	Liu and van Ryzin (2008)	Cachon (2001)	Boudreau et al. (2003)
8	Boyaci and Ray (2003)	Gayon et al. (2009)	Su (2008)
9	Gallego and Phillips (2004)	Chan et al. (2006)	Bolton and Katok (2008)
10	Tomlin (2003)	Choi et al. (2004)	Wang and Gerchak (2001)

in *M&SOM*, we performed further text mining to capture 10 topics. The text mining words for each topic are tabulated in Table 5. (The symbol "|" captures logical "or" statement in R.) Their trends, as quantified by the fraction of our domain papers whose abstract or keywords contain specific word stems, are shown in Figure 1. We segment the topics in three groups based on their trends (as measured by the least-squares best-fitted dotted lines shown in Figure 1) and also mention the most cited papers for each topic.

Topics with increasing popularity include the following word stems:

1. *Sourc|Procur|Glob|Decentr.* The top three most cited domain papers studying these topics are Bitran and Caldentey (2003), Van Mieghem (2003), and Boudreau et al. (2003).

2. *Flexib|Dual|Option|Transship.* The top three most cited domain papers studying these topics are Tsay and Lovejoy (1999), Van Mieghem (2003), and Corbett and Klassen (2006).

3. *Empiric|Data.* This topic has the highest growth rate, almost tripling over the last 20 years. The top three most cited domain papers that mention empirical or data are Gans et al. (2003), Liu et al. (2010), and Gaur and Seshadri (2005).

4. *Contingen|Disrupt|Risk|Hedge|Mitigat.* The top three most cited domain papers studying these topics are Aviv and Pazgal (2008), Van Mieghem (2003), and Agrawal and Seshadri (2000).

5. *Sustainab|Emission|Carbon|Green.* The top three most cited domain papers studying these topics are Corbett and Klassen (2006), Wang et al. (2013), and Hu et al. (2015).

Topics with nearly constant popularity include the following word stems:

6. *Contract|Compet|Game|Pricing.* The top three most cited domain papers studying these topics are Bitran and Caldentey (2003), Aviv and Pazgal (2008), and Tsay and Lovejoy (1999).

7. *Suppl.* The top three most cited domain papers studying these topics are Tsay and Lovejoy (1999), Corbett and Klassen (2006), and Agrawal and Seshadri (2000).

8. *Behavioral.* The top three most cited domain papers studying these topics are Tsay and Lovejoy (1999), Gino and Pisano (2008), and Boudreau et al. (2003).

Topics with decreasing popularity include the following word stems:

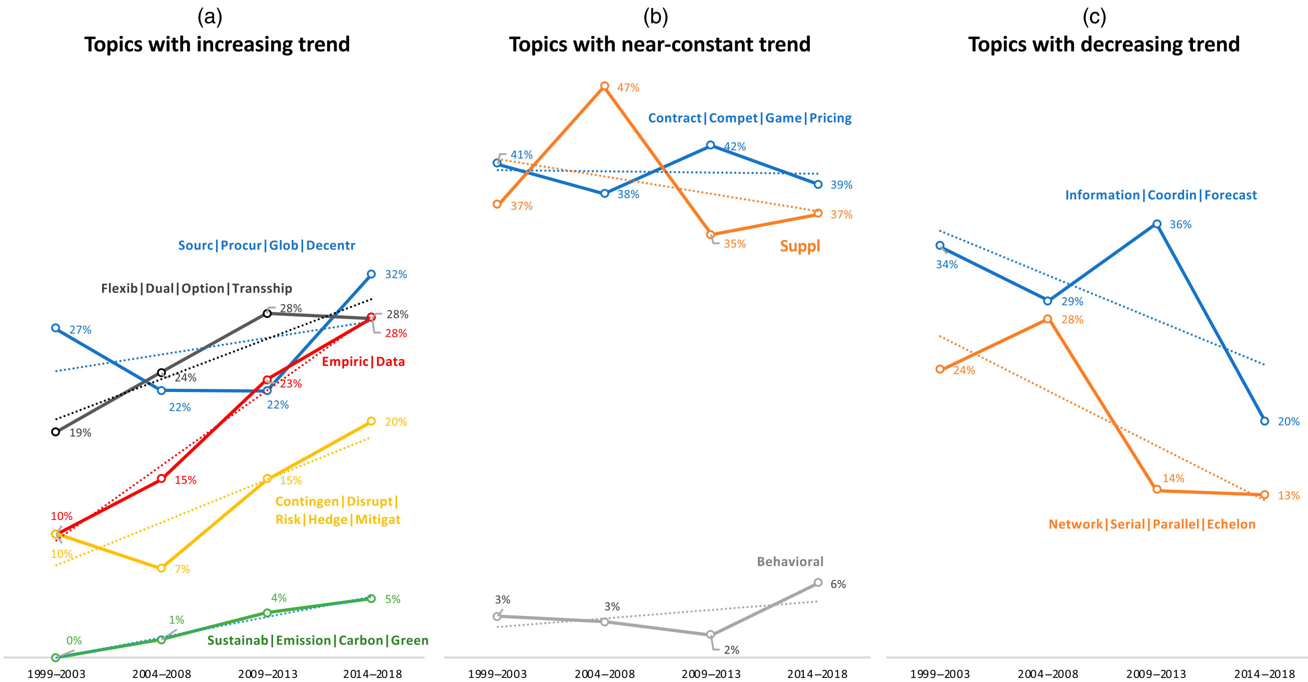
9. *Information|Coordin|Forecast.* The decreasing publication rate of these topics was surprising to us given their relevance in the Internet of Things (IoT) and digital supply chains (as we will discuss later during our projections). The top three most cited domain papers studying these topics are Gans et al. (2003),

Table 5. Glossary of the Word Stems (Ordered Alphabetically; Left) Used in Our Text Mining to Capture 10 Topics (Right)

Word stems	Research topics
Behavioral	Behavioral research
Contingen|Disrupt|Risk|Hedge|Mitigat	Contingent, disruption, risk, hedge, mitigate
Contract|Compet|Game|Pricing	Contracting, competition, game theory, pricing
Empiric|Data	Empirical, data (driven)
Flexib|Dual|Option|Transship	Flexibility, dual supply, options, transshipment
Information|Coordin|Forecast	Information, coordination, forecasting
Network|Serial|Parallel|Echelon	Networks, serial, parallel, (multi)echelon
Sourc|Procur|Glob|Decentr	Sourcing, procurement, global, decentralization
Suppl	Supply (management)
Sustainab|Emission|Carbon|Green	Sustainability, emissions, carbon, green

Note. The symbol "|" captures the logical "or" statement in R.

Figure 1. (Color online) Fraction of Capacity–Inventory Papers Whose Abstract or Keywords Contain Specific Word Stems



Tsay and Lovejoy (1999), are Corbett and Klassen (2006).

10. *Network|Serial|Parallel|Echelon.* Multiechelon inventory theory and network analysis has significantly decreased in this journal (although we believe that this trend may reverse). The top three most cited domain papers studying these topics are Graves and Willems (2000), Liu and van Ryzin (2008), and Van Mieghem and Rudi (2002).

Interestingly, while supply chains themselves became more global and collaborative, driven by several forces including cheap information technology, capacity and inventory researchers also started collaborating more across increasingly global teams (Figure 2). Table 6 shows how the dominant country (United States) actually has seen a reduction in the last lustrum, which is compensated by an increase in other countries, especially Canada, China, Hong Kong, and Singapore. Within the United States, most research activity originates from the handful of states that contain the most populated cities and metropolitan areas (Table 7).

4. Projections of Future Trends and Research Directions

To project future trends and research directions, we started by identifying “environmental and technological forces” (Table 8) that may drive innovations in inventory and capacity management of supply chains. Based on these forces, we then propose main research topics where inventories and capacities are instrumental. Some of these topics are further discussed in companion articles in this special issue.

4.1. Environmental and Technological Forces

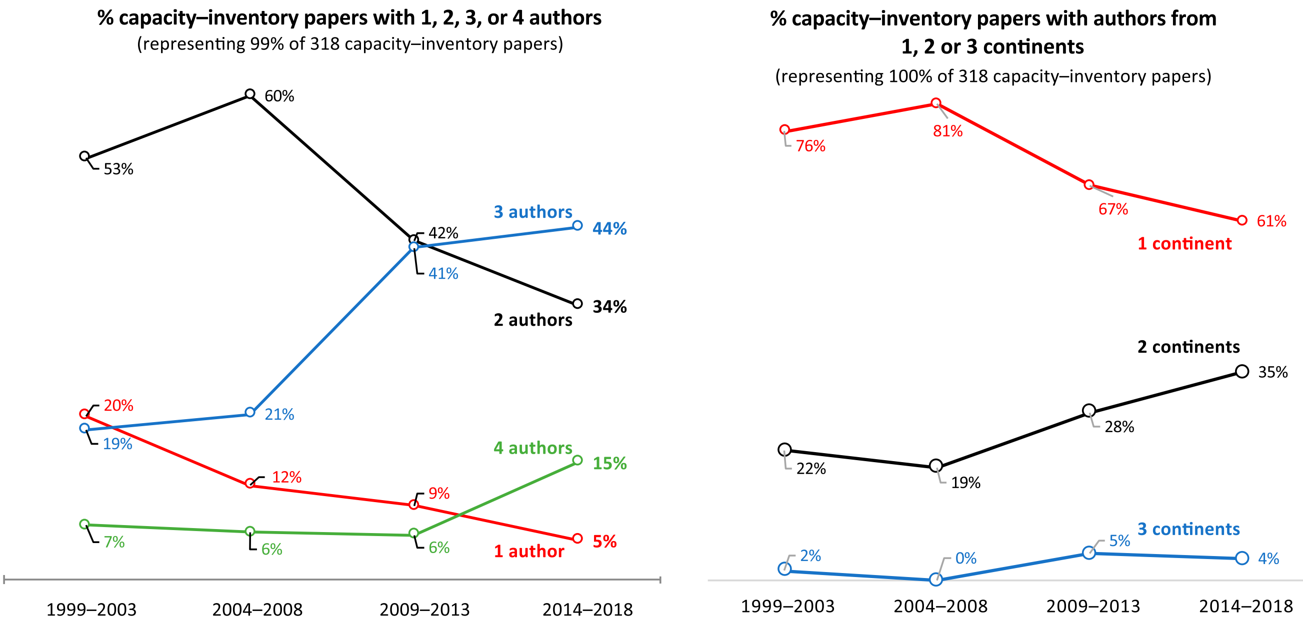
Abundant and ubiquitous computing power at continually lower cost has enabled technological advancements such as the internet, GPS, wireless communication, the IoT, robotics, and additive manufacturing (AM). These advancements have given rise to new business models that are continuing to fundamentally change production processes and supply chain configurations. Global information availability on the superior performance provided by top competitors like Amazon is raising customer expectations of ever-faster response times and more choices, ideally at the same price. Continuing globalization then may lead to increased competition and cost pressure. Following the rise of Brazil, Russia, India, China, and some other countries in the past years, many more countries may enter the global markets. At the same time, people on multiple continents may start realizing that we must be careful with our earth and its natural resources, which may be accompanied by increased attention toward sustainability and greenhouse gas emissions. Finally, we expect the current political instabilities to reoccur in the future so that supply chains will continue to face risks due to closed borders, changes in trade agreements, and international labor rules.

4.2. Main Research Topics

4.2.1. Control Towers and Dynamic Optimization of Existing Networks.

The faster responses to customer demands require smarter and faster operating decisions for real-time execution. Such instantaneous

Figure 2. (Color online) Capacity and Inventory Researchers Are Collaborating More (Left) in Increasingly Global (Right) Teams



coordination of supply chain flows could be realized by adopting the concept of *control towers*, similar to air traffic control that tracks the movements of all airplanes in the control tower's airspace and directs departures, routes, and landings. In their quest to meet all customer demands in time, companies could use such control towers to track progress in the fulfillment processes, prevent "collisions" (conflicts, delays), correct deviations, and allocate resources to new arriving demands. Real-time tracking of all processes involved is enabled by the IoT. Clearly, this real-time decision making at the executional level must be reflected in tactical planning and will require new research at both the executional and tactical planning levels. The challenge at the executional level is to make real-time decisions based on the best available information at that moment, probably by automating many decisions. Merging real-time sensor data imbedded in the IoT

Table 6. The Dynamics of Countries Represented in the Authors' Addresses of Capacity–Inventory Papers

Country	1999–2003	2004–2008	2009–2013	2014–2018	Total
1. Unites States	57	62	103	71	293
2. Canada	5	9	9	14	37
3. China	1	3	9	14	27
4. Hong Kong	3	5	7	8	23
5. India	6	3	6	5	20
6. Singapore	0	0	8	5	13
7. France	1	0	5	3	9
8. Netherlands	1	2	3	2	8
9. United Kingdom	0	2	2	4	8
10. Germany	1	0	1	5	7
11. Israel	3	0	1	0	4
13. Spain	0	1	2	1	4
13. Turkey	0	1	1	2	4
14. Argentina	0	0	2	0	2
15. Japan	0	1	1	0	2
16. South Korea	0	1	0	1	2
17. Sweden	1	0	0	1	2
18. Austria	0	0	1	0	1
19. Chile	0	0	0	1	1
20. Costa Rica	0	0	1	0	1
21. Lebanon	0	0	1	0	1
22. Thailand	0	0	0	1	1

Table 7. The Dynamics of U.S. States Represented in the Authors' Addresses of Capacity–Inventory Papers

U.S. states	1999–2003	2004–2008	2009–2013	2014–2018	Total
1. New York	17	14	19	13	63
2. California	11	14	22	15	62
3. Pennsylvania	6	9	17	12	44
4. North Carolina	6	9	17	10	42
5. Massachusetts	9	8	7	9	33
6. Illinois	9	5	12	6	32
7. Texas	3	6	11	5	25
8. Missouri	2	3	7	5	17
9. Michigan	3	2	7	3	15
10. Georgia	2	4	6	2	14
11. Indiana	4	2	3	3	12
12. Minnesota	2	3	3	3	11
13. Ohio	4	2	2	3	11
14. Virginia	3	3	3	0	9
15. Washington (WA)	0	1	3	3	7
16. Florida	1	2	1	2	6
17. Maryland	0	1	5	0	6
18. Arizona	0	0	3	2	5
19. New Hampshire	2	1	2	0	5
20. New Jersey	1	2	1	1	5
21. Colorado	2	0	1	1	4
22. South Carolina	0	0	1	3	4
23. Washington, DC	0	0	2	2	4
24. Wisconsin	0	1	1	2	4
25. Connecticut	0	0	3	0	3
26. Oregon	1	2	0	0	3
27. Tennessee	0	0	1	1	2
28. Iowa	1	0	0	0	1
29. North Dakota	1	0	0	0	1
30. Utah	0	0	1	0	1

with abundant *computing power and AI* may assist these smart operational decisions.

Data-Driven Machine-Learning Decision Models. There is tremendous need for scalable supply chain optimization algorithms to respond to dynamic information, that is, to perform data-driven reoptimization in a timely manner. The algorithms should be able to dynamically reallocate work to different plants, reroute products to different markets, and redirect replenishment orders to different supply sources when real-time data demonstrate shifted demand and supply conditions. Such dynamic automation resembles Google Maps' adaptive driving guidance service, which automatically recalculates and updates suggested routes when road conditions change or when the driver skips or misses a particular step on the original route.

Table 8. Environmental and Technological Forces That May Lead to New Developments in Capacity–Inventory Management

Environmental forces
1. Faster response and more customer choices
2. Increased globalization and competition
3. Less greenhouse gas emissions and better use of scarce natural resources
4. Political instabilities
Technological forces/enablers
1. Ubiquitous computing power
2. Internet of things
3. Artificial intelligence
4. Additive manufacturing
5. SPEED factories
6. Physical internet

While classic capacity and inventory control has studied these types of decisions—for example, dynamic scheduling of make-stock queues, dynamic inventory transshipments, and expediting or dual transportation mode models—they typically have assumed stationary demand distributions. When the demand environment is nonstationary, or its distribution is unknown, the form of the optimal policy is often difficult to identify because of the curse of dimensionality in the underlying dynamic program. Even if one can identify some policy structure, the policies are likely state dependent and pose enormous computational challenges. To solve these complex optimization problems on an industrial scale, especially in a nonparametric demand environment, machine/deep learning techniques could generate quick heuristics. This so-called prescriptive machine learning is developing fast, especially in the fields of computer science/AI, electrical engineering, and statistics.

The promise of machine learning includes general-purpose algorithms that, in principle, can readily be applied to many problems without years of specialized research to tailor the solution approach, and hence it is scalable. In practice, the generic nature of these algorithms may result in worse performance than the heuristics tailored to the specific problems (Gijsbrechts et al. 2018). In practice, one must decide which is better for the situation at hand: (1) quick, automated heuristic decisions that work; (2) optimal or human decisions that require much work and time; or (3) a combination of automatically offered options that are traded off by a human.

We expect option (3) to be the desired choice in many situations: the control tower would suggest actions on a manager's or operator's mobile device, but the decision maker could supplement intuition and other information to make necessary adjustments. This corresponds to typical usage of Google Maps routing: a driver may choose not to follow the suggest route based on experience or real-time road conditions, and use the automated routing guide only as a suggestion. Similarly, when assigning ambulances, an ambulance dispatcher would first obtain a suggested assignment from a decision support system and then manually adjust that suggestion based on the real-time information of ambulance availability.

We believe that human decision making, augmented by data-driven decision models suggesting real-time actions, will remain the desired approach in important settings. Although airplanes today greatly rely on automatic pilots, who would board a fully autonomous airplane without a human pilot? In complex operations, algorithms rarely can anticipate all possibilities economically. It remains desirable for the human decision maker to understand and judge whether the suggested actions make sense. Experience, common sense, intuition, and insights derived from structured models can rarely be replaced by a fully automated solution. Intervention is desired, if not necessary, when we detect stupid solutions due to input or algorithm errors. Although an automated GPS-routing software provides great convenience the majority of the time, who would follow an automated routing direction if it pointed into the ocean?

Fortunately, there has been increasing effort in developing explainable AI and interpretable machine learning (Pavlus 2019). This is encouraging, as the machine-learning algorithms may tackle problems that are intractable using the traditional optimization tools. Analyzing their output may generate insight into which variables are significant and which can be ignored. This, in turn, may help us enrich analytical models to develop deeper insights, as illustrated by Gijsbrechts et al. (2018) in the context of dual sourcing. It is also fortunate that this new direction aligns with the observed increasing trend of Topic 3 (Empiric|Data) in Section 3. This also may further increase the interest in Topic 8 (Behavioral) and, more specifically, people-centric operations, on which *M&SOM* has an upcoming special issue.

Structural Analysis and Insights. To improve our understanding of the main trade-offs and sharpen our intuition necessary for human decision making and system design, we need to continue developing structured models and characterizing optimal decisions. For instance, order-up-to policies, which are optimal in controlled stylized settings, remain useful in practical complex settings because of their simplicity and good (enough) performance. Similarly, demonstrating that an (r, q) policy is well approximated by a newsvendor and economic order quantity solution enhances our understanding and its practical implementation. We believe any efforts along this direction are worthwhile.

These quests will likely generate a resurgence of research in Topic 9 (Information|Coordin|Forecast) and Topic 10 (Network|Serial|Parallel|Echelon), which have experienced some decline in the trend analysis in Section 3. Indeed, we may witness an upward spiral evolution in research focus, where topics return yet at a more advanced level of analysis. Operations research often is about decision support tools. With IoT and mobile data, the new models and tools will enable synchronized, adaptive network support tools and personalized offerings. At the same time, our work is also about generating insights. Predictive analytics is similar in nature to performance evaluation of a given control policy (parameter). Traditionally, this involved stochastic processes to compute steady-state performance measures such as the distribution of waiting time, inventory, or backorders. Prescriptive analytics is similar to policy optimization, using dynamic programming and other optimization tools based on the performance evaluation methods. Both performance evaluation and optimization thus may return yet perhaps at a more advanced level: going from a traditionally parametric steady-state regime to a nonparametric transient regime.

4.2.2. Topics on Changing Production and Supply Chain Landscapes.

Local, Small-Scale Production and Collaboration Platforms. Offering more customer choice with fast response times can be realized from locations in close proximity of customers that either stock almost complete products or process the last (postponed) customization steps. New production technologies such as AM, robots, and small, local "SPEED" factories (Boute et al. 2019) are enabling forces for this development.

AM enables a globally operating company to invest in new product development while producing in local AM facilities. In contrast to traditional "subtractive" manufacturing, AM may also reduce greenhouse gas emissions. Local SPEED factories produce to order and are designed such that they can quickly respond to a high variety of demands.

This trend bears some similarity to the music industry, which originally had a supply chain with centralized production of physical products (record albums/tapes/CDs) that were distributed through distribution centers to retail stores. Today, that physical supply chain is largely replaced by a digital service chain, where consumers can download or stream music on demand. Similar transformations can be seen in the book and media industries, where readers can download, or view in real time, the e-version of the content.

When the end-product remains physical, production capabilities must remain, but new technologies enable more network configuration choices that spur new research: When is local production better than centralized production accompanied by a distribution network? What are the optimal number and capacity of local factories? Should local factories be owned or used as a service by third parties, perhaps enabled by three-dimensional (3D) printing? The latter outsourcing model raises new questions on how to design a licensing system (for intellectual property [IP] protection) that benefits all parties, as investigated by Westerweel et al. (2019) in the context of spare parts.

The physical supply chain may also coexist with the digital chain, as in the book industry. For such settings, mathematical models are needed to find the optimal mix in the hybrid chain. For example, Song and Zhang (2019) study the optimal design of spare part logistics systems in the presence of 3D printing. In their model, each part can either be supplied from stock or be printed on demand by a local 3D printer with finite capacity. The authors determine the optimal partition of parts that should be stocked versus printed. Their analysis reveals that the stock and print options are complementary. Although the print option cannot completely eliminate the need for the stock option, it does reduce that inventory significantly even though the optimal utilization of the 3D printer is quite low. Such models offer valuable insights to managers.

Digital technologies and additive manufacturing may give rise to new *production platforms* on which product designers, material suppliers, local manufacturers, and logistics providers all interact. Such new "ecosystems" may continue to stimulate research on contracting and coordination (including IP licensing and data security) and supply management, the two topics with highest research activity over the last 20 years as observed in Section 3.

Omnichannel Demands and Order Fulfillment. Continued development of e-commence, including mobile pay, apps, and perhaps drones for last mile delivery, can transform the traditional system where retail stores stock mass-produced items to an omnichannel system where customers buy both online and offline. Customers' quest for instant gratification forces e-tailers to find innovative configurations to fulfill online orders efficiently: from setting up separate pickup stations for online purchased items within local retail stores to fulfilling both demand streams from local store inventory with possible prioritization. These new supply chain configurations can benefit from more research that can build on classic operations principles: A new e-tailer may start with a simplified centralized supply chain without physical stores. If successful and growing, it may be better to set up central warehouses and regional distribution centers, similar to Amazon's evolution.

We expect our classic models to be augmented to study more responsive and adaptive supply chain configurations. Exploiting big data also may highlight the need to incorporate nonstationary and correlated demand patterns. Such research efforts may result in an upward change in the trends of Topics 6, 9, and 10 in Section 3.

4.2.3. Capacity and Inventory Decisions Related to Responsible Operations.

Closed-Loop Inventory Systems. When resources become scarce, responsible resource use becomes more important. More can be done with existing resources by reusing products, packaging, components, and materials. The traditional practices of reusing containers and wooden pallets may extend to other parts of the supply chain. For example, a consumer product manufacturer designed reusable containers to sell detergent and other consumables. Upon consumption, customers return the container to standard collection boxes that are picked up by the manufacturer for cleaning and reuse. Product staples themselves could also be designed for longer use (life-cycle management) and such that reuse is facilitated. As manufacturers continue to develop innovations to facilitate closed-loop supply chains, the upward trend in Topic 5 (Sustainab|Emission|Carbon|Green) may continue and revive research on closed-loop inventory systems, which were extensively studied 10–20 years ago. Another way to derive more value out of the same resources is by increasing their utilization when sharing them with groups of users. This may connect responsible operations to models of a sharing economy.

Physical Internet. Reusing and sharing resources may also limit if not reduce greenhouse gas emissions and global warming. We expect transportation to gain in importance both in practice and in research. In addition to utilizing low-emission transport modes, supply chains can be configured to reduce transportation. Some product components travel more than 40,000 km from raw material to their final customer. Adding a carbon tax would internalize the externality cost imposed on the environment and incentivize companies to produce locally, that is, in the same region, state, country, or even continent as the local customers. Such "local-for-local" supply chains require less transport than traditional remote production. Finally, transport itself could be organized in a smarter way. For example, industries could adopt and share a *physical internet* that transports physical products through a store-and-forward network, similar to how the internet moves digital information (cf. Ballot et al. 2014). One would simply enter products, together with destination information, at an entry point and the physical internet would deliver them within a reasonable time.

Differentiated Service and Pricing. More choice and faster response times typically do not come for free. Nor do all customers need, or are they willing to pay for, both all the time. Therefore, service and price differentiation may gather more attention in this new environment. New mechanisms are needed to give priority in production and transportation planning and in inventory allocations to those orders for which customers are willing to pay more. Similarly, one may offer lower prices or discounts to customers who are willing to accept reused products or products containing reused components. This may lead to a renaissance of service and price differentiation research, probably augmented with real-time data and decision making, perhaps reversing the recent downward trend in Topic 6 (Contract|Compet|Game|Pricing) in Section 3.

4.2.4. Resilient Supply Chain Design. Supply chain design includes deciding on production locations and on how to serve customers in certain locations or countries. These decisions should be based on forecasts that include the long-term political and economic situations of those countries. Short-term risks that can be predicted or anticipated, for example, a temporary border closure or strike, can be mitigated by temporarily increased inventory levels at specific points in the supply chain. Longer-term risks, for example, a change in a country's political situation, can be mitigated by building redundancy (dual or multisourcing) in the supply chain. Political risks, such as Brexit and changing tariffs associated with U.S.-China trade wars, may increase bullwhip effects.

We expect resilience and risk management to become more important in the coming years. This may increase interest in, for example, network planning to address the trade-off between off- and near-shoring. Such models may consider AM as a potential enabler for localized capacity. Research in this direction may continue the upward trend of Topics 1 (Sourc|Procur|Glob|Decentr), 2 (Flexib|Dual|Option|Transship), and 4 (Contingen|Disrupt|Risk|Hedge|Mitigat) discussed in Section 3. The future will tell to what extent supply chain configurations will be more global, more locally resilient, or some hybrid combination.

5. Conclusion

We reviewed capacity–inventory papers published in the first 20 years of *M&SOM*. Text mining appeared to be an appropriate method to select these papers and to show the shares of 10 popular topics and their trends in the past 20 years (see Section 3 and Figure 1). We found that roughly 50% of all papers published in *M&SOM* belong to the capacity–inventory domain, which is more than what we expected beforehand. Next, we made a projection of future research topics within capacity–inventory research. We expect that the 10 popular topics of the past 20 years will remain important, possibly with a new focus. In addition, relatively new topics are poised to become important, such as machine-learning decision models for capacity–inventory decisions; the trade-off between automated and human decision making; new concepts for local, small-scale production; mixed digital–physical supply chains; and the physical internet.

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