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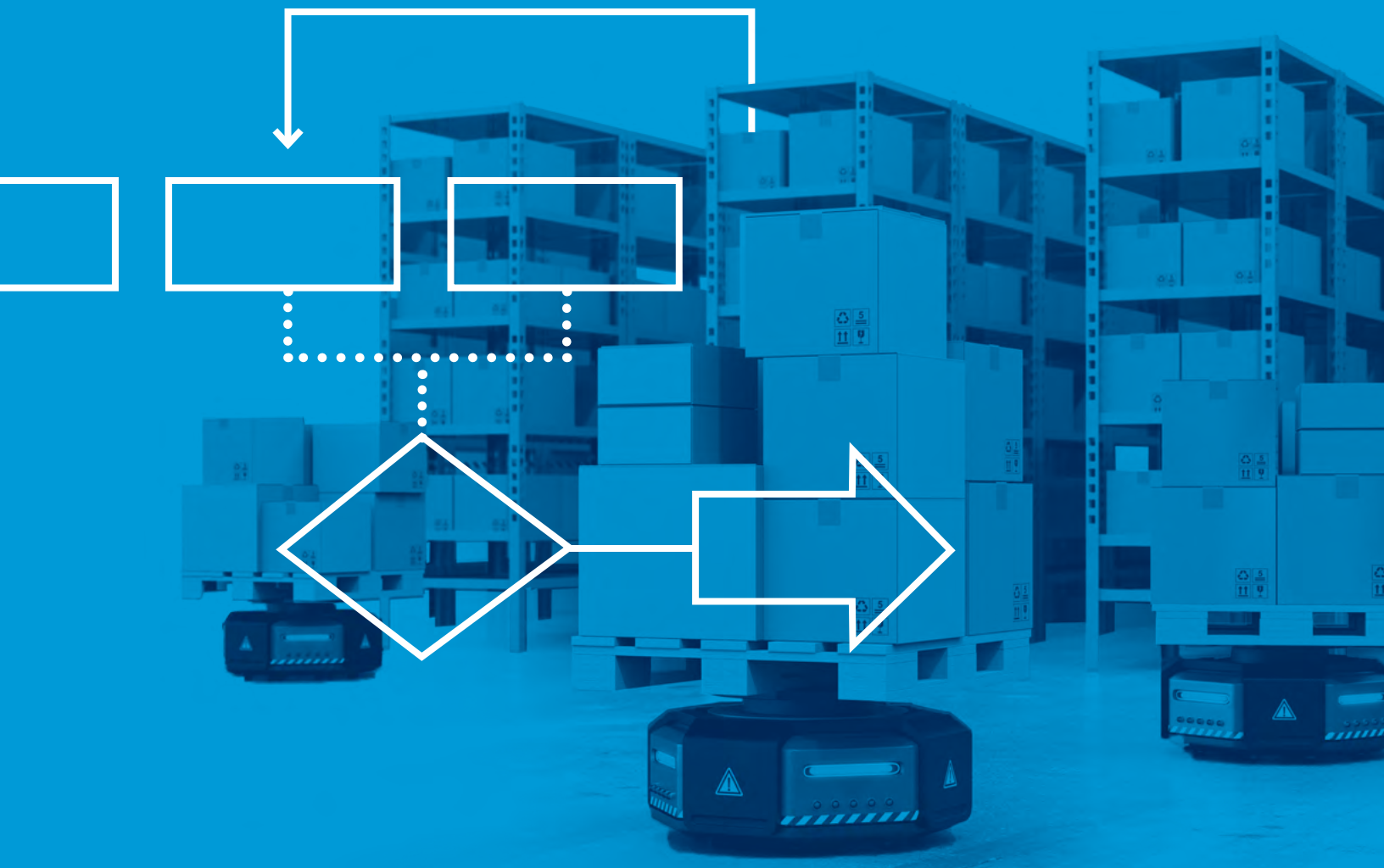
The Gartner Supply Chain Top 25 for 2020



Supply chain leaders exhibit adaptability and resiliency, especially during times of disruption. The Gartner Supply Chain Top 25 highlights companies possessing these and other differentiating capabilities, and provides people, process and technology insights that CSCOs can use to compete.

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Key findings

- Major methodology changes were introduced in 2020, including a conversion to return on physical assets (ROPA) from return on assets (ROA), a reduction in the weighting of the inventory measure and an increase in weighting to the environmental, social and governance (ESG) (previously corporate social responsibility [CSR]) measure.
- Six new companies joined this year's list — Lenovo, AbbVie, British American Tobacco, Reckitt Benckiser, Biogen and Kimberly-Clark.
- The three key factors that differentiated leading supply chains this year were being purpose-driven organizations, business model transformers and digital orchestrators.
- Similar to last year, a new No. 1 emerged. For 2020 Cisco Systems claimed the No. 1 spot, followed by Colgate-Palmolive, Johnson & Johnson, Schneider Electric and Nestlé. The 2020 Masters are Amazon, Apple, McDonald's, P&G and Unilever.

Recommendations

Chief supply chain officers (CSCOs) and supply chain leaders can learn from the strategy and leadership of the top global supply chains, and:

- Clearly define and communicate your supply chain's broader purpose in the world to inspire customers, employees and partners to act ethically and sustainably in support of the global community.
- Position your organization to be a disruptor by infusing agility into existing capabilities or acquiring startups offering the expertise and DNA necessary to compete in new or reinvented markets.
- Create a digital orchestration culture in your organization by investing in rapid and open innovation that is sourced from both internal talent and external partners with specialized skills and technologies.

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Analysis

This year, we took a deeper look at the program methodology, reflecting the voice of the community on emerging facets of supply chain leadership. In our 16th edition of the Supply Chain Top 25, we have an impressive group of leaders with new lessons to share, including a diverse set of six new entrants.

In past years, our Top 25 leaders have demonstrated significant capabilities in agility and disruption management. In 2020 of course, we have experienced one of the most significant disruptions in a lifetime. Many organizations felt the financial impact of the disruption beginning in early 2020, after we pulled all the financial information used as part of the business measurement component of the methodology. The peer and analyst voting components occurred in March and April of 2020 and reflect voters' perspectives on how companies dealt with the pandemic. It is instructive to see how many of the Top 25 companies have reacted and positioned themselves for success during and post disruption.

With substantial portions of the global economy closed because of the COVID-19 pandemic, we are seeing unemployment and negative economic growth rates on a scale not seen since the early 20th century in some cases. As countries around the world reopen their economies, massive uncertainty remains about how much activity will ramp up, as the public navigates a new world of social distancing, face masks and a fear of resurgence of infections. Countries are bracing for historic economic contractions. Many companies have abandoned profit forecasts.

Scenario planning is crucial for recovery (see "What Western Businesses Can Learn as China Comes Out of COVID-19 Lockdown"). Leading companies are defining scenarios to predict how markets will recover postlockdown with a focus on accelerating competitiveness in the recovery curve, while also building in risk-mitigation strategies in case of a second wave of COVID-19. Leaders need an agile, or adaptive, strategy that allows the supply chain organization to sense and respond to changes in the business context as they happen (see "Winning in the Turns: A Supply Chain Action Guide"). They also need to think long term and forecast for the upturn.

Notable Trends

Each year, our analysts research the supply chains of hundreds of companies. Through this work, we note categories of activity such as: What leaders are focusing on, where they are investing time and effort, and what can be applied broadly? Three key trends stand out this year for these leaders that are accelerating their capabilities and further separating themselves from the rest of the pack (see Figure 1).

Figure 1. 2020 Supply Chain Leadership Trends

Purpose-Driven Organizations. Last summer, the Business Roundtable (BRT), an organization that includes nearly 200 large companies, issued a game-changing statement of purpose for the corporation. This influential group expanded the objective from merely maximizing shareholder return to delivering value for the benefit of all stakeholders — customers, employees, suppliers and communities, in addition to investors.

While many viewed this statement as aspirational at the time, in the age of COVID-19, it has been a marvel to witness the strength and creativity of the supply chain community rallying around a purpose (pandemic response), and demonstrating this aspiration by keeping our society fed, supplied and healthy. We've seen apparel companies manufacturing personal protective equipment (PPE), adult beverage companies making hand sanitizer, industrial companies shifting to producing ventilators and airlines converting dormant warehouses into food bank processing centers. Just as impressive are the short time frames in which these shifts have occurred — in weeks, for what normally takes months or quarters to plan and execute.

Even before the pandemic occurred, supply chain teams at leading companies defined their work using the language of purpose. These companies recognize that solving the world's largest problems only works through partnership with others in the broader community, as well as through their own radical transparency. They are pursuing this greater purpose while running efficient and effective supply chains. However, the pandemic also exposed organizations that prioritized cost over agility and resiliency.

Unilever has stood out for its corporate goal of making sustainable living commonplace. Its supply chain team regularly highlights that brands with purpose grow faster and employees with purpose thrive. Palm oil, a key input to many of Unilever's personal care products, is typically sourced from places where deforestation and disenfranchisement of smallholders is an issue. Its sourcing organization is leveraging advanced tools, such as geospatial mapping combined with mobile device signal tracking, to certify "deforestation-free" palm oil supply.

The concept of circular economy (CE) models has also gained traction as part of a larger trend toward running ethical and sustainable supply chains. Gartner's "Future of Supply Chain: Reshaping the Profession" research shows that 70% of companies are making some level of investment in CE models. Leaders such as Cisco and Schneider Electric are focused on recycling components from old equipment back into new offerings or, at a minimum, recapturing some value from them before safely disposing the remainder. Likewise, consumer products giant, P&G currently recycles nearly all of its manufacturing waste and has set ambitious conservation goals for water, forests and other natural resources. In terms of postconsumer waste, it is turning feminine products into spill abatement solutions and used diapers into spoons.

Business-Model Transformers. One of the largest external forces impacting corporate supply chains is a dynamic competitive landscape that is driven by a combination of expanded customer expectations, new market entrants from existing industry ecosystems and the emergence of nontraditional competitors. Gartner's Future of Supply Chain Survey conducted in late 2019 found that more than half of supply chain organizations, across a range of industries, believe that they are at risk of disruption in the coming years. Undoubtedly, the aftermath of the COVID-19 event will drive two outcomes — development of new, agile business models, as well as leaving less-responsive business models and, potentially, industries in the history books. To thrive, supply chains must be enablers of these changes by possessing solid operational models and transformational capabilities.

Leading supply chains have positioned themselves as the disruptors to traditional business models, either through reinvention of their offerings and the ability to deliver them with agility or by acquiring startups that offer the expertise and DNA necessary to compete in new or reinvented markets. An example of this is Nike's acquisition of predictive analytics company Celect to better understand and react to consumer behavior data.

L'Oréal, with its ability to personalize customer offerings, is a great example of a traditional consumer products company that is midtransition to operating as a retailer with both physical stores and robust direct-to-consumer capabilities. Amazon is a serial disruptor, developing diverse capabilities such as maintenance, repair and operations (MRO) supplies, and pharmacy services — where supply chain investment, such as last-mile logistics, is a competitive advantage. Intel has transformed from a computing-centric business based predominantly on its own product and manufacturing process technology to a diverse portfolio of businesses that demand advanced supply chain analytics and orchestration. These range from automotive electronics to smart infrastructure and custom hyperscale data center solutions that integrate its own and many other's designs.

Another underpinning of these disruptor success stories is the ability to deeply understand the voice of the customer (VoC) and deliver personalized offerings to ensure an elevated customer experience (CX). Lenovo's supply chain team has created mechanisms to sense and translate a digital VoC into direct actions required by its manufacturing and supply base (e.g., proactive quality check). It is also creating closed-loop feedback to R&D on the design of its future products.

Digital Orchestrators. In the current environment, the natural tendency of many companies is to pull back spending, including money tied to transformational programs. Advanced supply chains are pressing forward and, in some cases, accelerating investments in real-time visibility, planning and agile supply chain execution capabilities, well-suited for supporting uncertain demand mixes and volumes. Leading companies in the Supply Chain Top 25 are early, and frequent, adopters of digital technologies. More importantly, these investments enable business capabilities and outcomes that allow them to thrive in even the harshest economic conditions.

Gartner's most recent Supply Chain User Wants and Needs Study shows advanced analytics and big data applications voted as the most important and frequently adopted (~70% of the population) digital capabilities. Other important, and frequently, adopted technologies include robotic process automation (RPA), artificial intelligence (AI) and/or machine learning (ML), and the Internet of Things (IoT) applications. Robots have also proliferated on the floors of factories and warehouses, often paired with automated guided vehicles (AGVs) to shuttle materials and finished items between stations and out the door. In addition to automation and augmentation in operations, many of the Supply Chain Top 25 also have some form of connected products in their portfolios to increase the value-add of customer offerings. These investments are often made as part of a shift toward digital business models.

Many leaders, such as Cisco, Johnson & Johnson (J&J) and Diageo, are near completion of next-generation ERP systems that replace a patchwork of older versions and one-off systems that were developed by individual business units or inherited through mergers and acquisitions. This foundational platform enables them to simplify and standardize processes for greater capability now, and to more easily upgrade and extend capabilities in the future. These leaders have also invested in data, recognizing that quality data is the fuel for high-performance analytics. This foundation is a key enabler to unlocking value through faster and more successful product launches, a consolidated VoC and more synchronized upstream supply planning.

These remarkable advancements are, of course, impossible without a digital-ready workforce. Leaders on the Supply Chain Top 25 have shaped cultures based on rapid and open innovation that is sourced from both internal talent and external partners with specialized skills and technologies. The supply chain in organizations such as HP Inc., Intel and Schneider Electric have created large-scale academies aimed at developing data analytics and other digital skills in their workforces. Many others speak of democratizing data by granting broader access to internal and external information that can be mined for greater insight by users across supply chain roles. Many of the Supply Chain Top 25 companies have close relationships with universities to shape curricula and create a pipeline of skilled candidates. Others have stepped more broadly into partnerships with local secondary schools, community colleges, governments and employers to foster a healthy labor ecosystem for everyone involved.

Inside the Numbers

Supply Chain Masters: Five Companies Leading the Way

In 2015, we introduced a new category to highlight the accomplishments and capabilities of long-term leaders. We refer to these companies as Supply Chain "Masters" and define them as having attained top-five composite scores for at least seven out of the last 10 years. To be clear, this category is separate from the overall Supply Chain Top 25 list, but it is not a retirement from being evaluated as part of our annual research. To the contrary, if a Masters company were to fall out of having a top-five composite score for four of the next ten years, it would lose this designation and be considered as part of the Supply Chain Top 25 ranking, in the same way as any other company in our study.

All of last year's Masters, Amazon, Apple, McDonald's, P&G and Unilever, qualified for this category again this year (see Figure 2).

Figure 2. Gartner Supply Chain Masters 2020

Amazon
Years with top-five composite score

2011 2012 2013
2014 2015 2016
2017 2018 2019
2020

Apple
Years with top-five composite score

2010 2011 2012
2013 2014 2015
2016 2017 2018
2019 2020

McDonald's
Years with top-five composite score

2011 2012 2013
2014 2015 2016
2017 2018 2019

P&G
Years with top-five composite score

2010 2011 2012
2014 2015 2016
2017 2018 2019
2020

Unilever
Years with top-five composite score

2011 2012 2013
2014 2015 2016
2017 2018 2019
2020

Amazon

As one of the prominent players in the COVID-19 response, Amazon has had its share of good and bad press. Despite these and other challenges, Amazon continues to drive rapid growth across its portfolio, ranging from retail to cloud, devices and media. Customer centricity, supply chain capability and an innovation culture are at the core of its efforts and have led to a range of attention-grabbing capabilities. These vary widely including:

- Ever-faster, last-mile delivery capabilities, including next-day and same-day services, as well as the ownership of delivery with reports indicating that Amazon now delivers nearly half of its own packages, rather than relying on third-party providers.
- The hiring of 175,000 additional workers during the initial peak of the COVID-19 crisis to ensure customers continued to receive everyday necessity items and medical supplies.
- Scaling of the grocery-focused retail concepts including the new 10,400 square foot Amazon Go Grocery "just walk out" store in Seattle and microfulfillment capabilities.

A key area of opportunity remains — ESG, however. It is seeing increased emphasis within the business including stated goals to be net zero carbon by 2040 and reaching 100% renewable energy by 2030. Given Amazon's innovative track record, as well as efforts already made in terms of a drive toward more sustainable packaging and the purchasing of 100,000 electric delivery vans from Rivian, we look forward to seeing the company delivering on and, hopefully, accelerating the achievement of these goals.

Apple

Despite the pandemic, Apple is committed to and continues to make investment in new products in areas such as services, wearables and accessories. There is no doubt that short-term supply will be impacted, as virtually all iPhones are made in China, in the so-called iPhone City in Zhengzhou by Pegatron, near Shanghai.

Apple has been a long-term leader in focusing on what is important when it comes to customer experience. Apple built its business models on the ability to generate revenue (and ultimately profits) based on deeply knowing its customers (and their preferences) by leveraging the data collected from its myriad of users. This is "baked into" its product designs and ongoing enhancements, as well as services.

Apple's sustainability team has driven significantly improved visibility and performance on ESG issues beyond its first-tier supply base. Apple is committed to ESG, reducing its carbon footprint by 35% since 2015. The new MacBook Air and Mac mini have enclosures made from 100% recycled aluminum, which required a new alloy to be developed. All of Apple's offices, retail locations and data centers run on renewable energy. The supply chain community continues to recognize Apple's leadership, awarding it a Top 5 peer vote score again this year.

McDonald's

McDonald's has used its extensive supply chain ecosystem to disrupt its value proposition to consumers, focusing on more fresh, sustainable and even vegan options. This has included the roll out of fresh beef across its network of approximately 14,000 store locations across the U.S. and a commitment to sourcing 100% cage-free eggs by 2025. Critical to the successful deployment of these changes has been the engagement and support of McDonald's existing ecosystem of suppliers. One key is the ability to manage trade-offs across the ecosystem. For example, the switch to fresh beef has cost implications for the meat suppliers but it has been critical to enabling the highest comparable sales growth the business has experienced in more than 10 years.

The McDonald's team also runs innovation days that include suppliers as part of a broader effort to continually improve menu offerings and supporting processes. Another key focus for McDonald's supply chain is using its scale for good. The organization, in partnership with suppliers and noncorporate partners, is focused on sustainable sourcing, decreasing packaging waste and reducing carbon emissions.

McDonald's is also responding to the pandemic by revamping the quick-serve restaurant experience. In the Netherlands, tests include meal trolleys and designated waiting spots to separate customers. In the U.S., McDonald's has already changed nearly 50 processes, including wellness checks, installing protective barriers, social distancing floor decals and providing thermometers to restaurants.

P&G

P&G continues its digital transformation by radically changing the way that work is done, while driving improved business results and productivity. A key example is in supply planning, where its innovation was recognized with a FICO Decisions Award in 2019. Using algorithm-driven, phase-in and phase-out optimization, P&G has optimized its product transitions, saving millions of dollars and allowing it to reduce time spent on supply chain initiative planning. The supply chain innovation has boosted analytics efficiency by 90%, reducing the weekly analysis time to less than five minutes.[1] P&G has also made changes in its supply network with redesigns in North America and Europe. These projects were multiyear and multisite, and impacted both manufacturing and warehousing.

Sustainability continues to be a focal point for the company through its Ambition 2030 goal, and it has made significant progress toward two of its flagship initiatives — zero waste and renewable energy. P&G is now purchasing 100% recyclable electricity in the U.S., Canada and Europe (its largest markets). Ninety-two percent of P&G's production sites are zero manufacturing waste to landfill with the remaining plants in the final waste qualification process.

In response to COVID-19, P&G has partnered with and supported more than 200 NGOs, agencies and world-leading relief organizations globally with cash and product donations in the tens of millions of dollars. P&G is also making critically needed nonmedical face masks in every region of the world, and has leveraged its R&D to quickly produce face shields to be used in hospitals and testing centers.

Unilever

Unilever continues to focus its supply chain around being "purpose-led and future-fit." Unilever is focused on supply chain transformation to drive increased agility for a rapidly changing market. A key area of change is in planning. Here, it is building a more responsive organization and using innovative technologies to enable shorter and more agile planning cycles to achieve shorter lead times and inventory reduction.

Unilever is also committed to using digital capabilities to expand sustainability capabilities. The company is actively developing and deploying technologies to disrupt and transform supply chain transparency. It is investing in satellite data, geolocation, blockchain, AI, and working with major tech firms and innovative startups to build new approaches to monitoring and traceability, extending from downstream operations to plantation or crop source. Digital is proving to be a key enabler to connect to the farmers who grow raw materials. Unilever leverages satellite data to assess and monitor deforestation risk, using digital tools and aerial mapping of smallholder plots of palm.

To ensure resilience during the COVID-19 pandemic, Unilever is using technology such as RPA crawlers and AI to comb through millions of deliveries and thousands of suppliers to spot potential risks or shortages.[2] Unilever also rapidly adapted deodorant lines to make hand sanitizer for hospitals, and committed to provide free soap, sanitizer, bleach and food to the value of £100 million.

The Masters and Supply Chain Top 25 Leading the Way With Lessons for All

Amazon, Apple, McDonald's, P&G and Unilever continue to demonstrate advanced lessons for the supply chain community. Along with the Masters category, the Supply Chain Top 25 offers a platform for insights, lessons, debates and contributions to the rising influence of supply chain practices on the global economy (see Table 1).

Table 1. The Gartner Supply Chain Top 25 for 2020

Rank	Company	Peer opinion[1] (151 voters) (25%)	Gartner opinion[1] (44 voters) (25%)	3-year weighted ROPA[2] (20%)	Inventory turns[3] (5%)	3-year weighted revenue growth[4] (10%)	ESG Component Score[5] (15%)	Composite Score[6]
1	Cisco Systems	470	574	300.7%	12.5	2.9%	10.00	**6.25**
2	Colgate-Palmolive	1113	532	68.8%	4.7	1.0%	10.00	**5.37**
3	Johnson & Johnson	885	454	77.6%	3.0	3.6%	8.00	**4.65**
4	Schneider Electric	567	453	63.0%	5.4	4.2%	10.00	**4.48**
5	Nestlé	1084	350	40.0%	4.8	1.2%	10.00	**4.44**
6	PepsiCo	857	385	47.9%	8.2	2.7%	10.00	**4.42**
7	Alibaba	991	316	106.7%	23.9	54.0%	0.00	**4.39**
8	Intel	583	488	37.4%	3.5	5.8%	8.00	**4.12**
9	Inditex	737	351	34.7%	4.6	6.8%	10.00	**4.11**
10	L'Oréal	677	252	71.1%	2.8	7.4%	10.00	**4.01**
11	Walmart	1333	324	13.2%	8.5	2.4%	7.00	**4.00**
12	HP Inc.	296	389	51.1%	8.5	5.5%	10.00	**3.87**
13	Coca-Cola	1195	207	75.4%	4.4	0.0%	6.00	**3.74**
14	Diageo	403	280	41.4%	0.9	6.2%	10.00	**3.49**
15	Lenovo	397	307	16.9%	11.2	7.0%	10.00	**3.44**
16	Nike	768	265	47.2%	4.0	6.7%	6.00	**3.35**
17	AbbVie	128	30	262.4%	4.1	7.6%	5.00	**3.20**
18	BMW	575	182	24.8%	3.9	4.2%	10.00	**3.17**
19	Starbucks	799	202	52.6%	13.0	7.7%	4.00	**2.99**
20	H&M	412	161	22.4%	2.8	7.7%	10.00	**2.95**
21	British American Tobacco	154	56	85.6%	0.7	18.1%	9.00	**2.90**
22	3M	624	207	54.1%	3.9	1.1%	6.00	**2.90**
23	Reckitt Benckiser	265	14	99.0%	3.8	8.2%	9.00	**2.79**
24	Biogen	79	27	152.2%	2.5	7.8%	7.00	**2.78**
25	Kimberly-Clark	534	80	34.6%	6.6	0.2%	10.00	**2.76**

(1) Gartner Opinion and Peer Opinion based on each panel's forced-rank ordering against the definition of "DDVN Orchestrator."
(2) ROPA: ((2019 operating income / (2019 Net property, plant, equipment + year-end inventory)) x 50%) + ((2018 operating income) / (2018 Net property, plant, equipment + year-end inventory)) x 30%) + ((2017 operating income / (2017 Net property, plant, equipment + year-end inventory)) x 20%).
(3) Inventory Turns: 2019 cost of goods sold / 2019 quarterly average inventory.
(4) Revenue Growth: ((change in revenue 2019-2018) x 50%) + ((change in revenue 2018-2017) x 30%) + ((change in revenue 2017-2016) x 20%).
(5) ESG Component Score: Index of third-party environmental, social and governance measures of commitment, transparency and performance.
(6) Composite Score: (Peer Opinion x 25%) + (Gartner Research Opinion x 25%) + (ROPA x 20%) + (Inventory Turns x 5%) + (Revenue Growth x 10%) + (ESG Component Score x 15%).
2019 data used where available. Where unavailable, latest available full-year data used.
All raw data normalized to a 10-point scale, prior to composite calculation.
"Ranks" for tied composite scores are determined using next decimal point comparison.
Source: Gartner

The Top 5

High-tech leader **Cisco Systems** comes in at No. 1 this year on strong revenue growth, strength in ESG, and recognition of leadership in the community opinion polls. Cisco's transformation from product-centric to offer-based, continues to drive multiple business models within the company. These digital businesses are supported by a digital supply chain that can take advantage of data and is predicated on security as a foundation. Supply chain security needs evolve, and Cisco has been on an improvement journey of its own, operationalizing the ability to monitor and mitigate partner IT security capabilities. In addition, Cisco has driven significant value in predictability in lead-time, cost savings and inventory reduction, while launching many new products, offers and services. Its ESG efforts include the CE. The key strategic focus is to design in the circularity, from the standpoint of material use, packaging, energy consumption, repair and reuse. The goal is to have all new Cisco products incorporate circular design principles by fiscal year 2025.

Consumer products leader **Colgate-Palmolive** is No. 2. Colgate-Palmolive's commitment in reducing its impact on the environment is evident in its effort to go beyond zero waste and be certified as "TRUE Zero Waste" through an external certification program owned by the U.S. Green Building Council (USGBC). Since 2017, 15 of its manufacturing sites have achieved TRUE Zero Waste certification, with 10 achieving platinum status, the highest level of recognition. Colgate-Palmolive received the 2019 Leadership Award from the USGBC "as an organization at the forefront of the green building movement," based on its TRUE Zero Waste certification accomplishments.[3]

As part of Colgate-Palmolive's effort to have all products 100% recyclable by 2025, it has launched the recyclable tube. Tube development took five years, including collaboration with the Association of Plastic Recyclers (APR) and Plastic Recyclers Europe (PRE) to be the first to officially certify a recyclable tube. In alignment with the company's values and sustainability goals, Colgate-Palmolive is sharing the technology with other companies through open sourcing to encourage all tube products to be recyclable.[4]

In response to COVID-19, Colgate-Palmolive has mobilized five of its manufacturing plants on three continents to produce 25 million bars of soaps for global agencies that will be specially packaged with instructions on proper handwashing to amplify the World Health Organization (WHO) #SafeHands message.

Prominent healthcare conglomerate **Johnson & Johnson** climbs five spots to No. 3. While J&J has been a mainstay in the Top 25 and a top-ranked life science supply chain, it is not satisfied with its accomplishments. J&J continues to look for ways to advance, seeking to define what a high-maturity supply chain looks like for the life science industry.

J&J's embrace of supply chain innovation is unparalleled in the life science industry, where innovation is usually reserved for product development. Its Supply Chain Innovation Engine, located in New Brunswick, NJ, is an example of how J&J puts innovation into practice. It's a physical space that allows collaboration between J&J's supply chain team, key partners and external experts. People who work there prioritize disruptive ideas that will improve healthcare.[5] To support the effort to treat COVID-19 patients, J&J is leveraging its 3D printing expertise. Its 3D printing expertise is detailed in its 2018 Chainnovator winning submission (see "Healthcare Supply Chainnovators 2018: Johnson & Johnson Wins for Its 3D Printing Center of Excellence"). By 3D printing manifolds, J&J is helping to alleviate the constraint of a limited supply of ventilators. These manifolds, designed by Prisma Health, allow two patients to share the same ventilator.

Climbing seven spots to No. 4 is industrial leader **Schneider Electric**. The French energy management and automation specialist continues its advancement in the Top 25 rankings. This move into the Top 5 is a remarkable achievement, considering that it only made its debut on the Gartner Top 25 four years ago.

Schneider Electric is continuing to execute its proven Tailored Sustainable Connected 4.0 supply chain (TSC 4.0) strategy. The company has successfully been building the foundational end-to-end supply chain processes and capabilities for many years. Now it is building advanced digital systems on that foundation. Schneider Electric EcoStruxure is a suite of tools and services to help in IoT development.[6] One of the core capabilities that it provides is connectivity across the business, providing support for better and faster decision making throughout operations.

A factor that has undoubtedly helped Schneider Electric to be recognized by its peers as a leader in supply chain excellence is its openness to share what it is doing. With its presentations in supply chain conferences, YouTube videos and a great number of articles about its supply chain journey, the company embodies the concept of Gartner Supply Chain Top 25 — to promote and make visible the supply chain profession.

With a top-five peer score (of non-Masters) and perfect ESG score, **Nestlé** lands at No. 5. Nestlé has a strong focus on customer centricity to drive growth and profitability with an emphasis on improving product availability on-shelf and online, and being the "partner of choice" with key customers. To improve product availability, Nestlé is investing in additional capacity and performance in select manufacturing facilities to increase agility, transforming its planning capabilities with demand-sensing technologies and integrating strategic collaboration with key customers.

Personalization is a key component in becoming partner of choice and Nestle is excelling in this area with Nestlé Nutrition, providing flexible packaging platforms to enable customization to quickly meet customer needs and commercial opportunities. This includes focus on late-stage differentiation drives to improve agility. Additionally, with Nestlé's acquisition in August 2019 of Persona, a customized vitamin-pack subscription service, it is now a major contender in this area.[7,8]

Movers and Shakers: No. 6 Through No. 15

This section of the ranking offers an impressive array of household names and a new entrant, all providing notable contributions to the discipline of supply chain management (SCM).

Food and beverage leader **PepsiCo** lands at No. 6. PepsiCo is leading the way in SmartLabel, the common industry platform that provides visibility to key information that consumers are focused on, including nutritional facts and certifications that support the highest levels of safety, purity and sustainability. Additionally, it is in-market with 50 SKUs containing digital watermarks that have bar codes embedded into packaging graphics that are imperceptible to the naked eye but can be read by point of sale (POS) mobiles and robots. The technology allows for plastic recycling sortation by scanning the item to determine its recyclability.[9]

On the sustainability front, PepsiCo North America is leading with 100% sustainably sourced potatoes and corn. PepsiCo's U.S. operations will be powered by 100% renewable electricity this year as part of its global goal to cut emissions by 20% by 2030. This is accomplished with solar panels, fork trucks that run on electricity instead of diesel, and a move to more electric vehicles, including delivery trucks that will be charged with renewable energy.[10]

PepsiCo activated its global resources to provide food and other essential relief to help those affected by COVID-19. Representing $45 million, the effort spanned more than 40 countries and involved working with 35 partners to support communities around the world.

Chinese retail giant **Alibaba** continues its rise, up six spots to No. 7. Similar to its largest Western competitor Amazon, supply chain is very much at the center of Alibaba's business. However, what differentiates the Chinese digital giant is the sheer scale at which it operates. Consider that, for its Singles' Day sales event on 11 November 2019, nearly 1.3 billion orders were placed across Alibaba's platforms, with a gross merchandise value of $38 billion in just 24 hours. Of this, the first 100 million orders were shipped in under eight hours.

Alibaba's sustainability efforts continue with 75,000 recycling depots set-up for consumers to drop-off unwanted shipping boxes and bags. The business is also leading retail supply chain efforts globally in terms of online-offline integration via almost 200 Freshippo (known as Hema in China) grocery-focused concept stores that enable fulfillment from store and delivery to consumers in as little as 30 minutes.

Chip giant **Intel** came in at No. 8, with a 2019 annual revenue increase of 1.58% from 2018. Intel's first-quarter 2020 revenue is significant in that it is 18.7% higher than in 2019, despite the global pandemic. Supply chain was credited with helping achieve this success. George Davis, CFO of Intel, said, "It's really heroic work, both at the supply chain level, we have a fantastic supply chain group, but also our manufacturing teams, keeping the factories up and running. Delivering 90% on-time commits in a quarter like this is really remarkable."[11]

Intel continues to drive customer-centricity with increased collaboration with customers to understand critical capabilities, alignment of the supplier ecosystem and reaching upstream to design-in the requirements as part of the product planning process. The resiliency of Intel's supply chain is not to be underestimated. A well-orchestrated and practiced process and system is able to handle many different types of disruptions. Sustainability leadership has been in Intel's DNA. One example is Intel's commitment to sustainable water management. Over the past two decades, Intel's sustainable water management efforts have returned approximately 80% of its water back to the community.

Inditex, best known for its Zara brand, landed at No. 9. The importance of supply chain operations to the fast-fashion giant was highlighted by the July 2019 elevation of former COO Carlos Crespo into the role of Inditex CEO. Crespo has been critical in driving the organization toward its digital supply chain leadership role through integration of store and physical operations, and vast product-level RFID deployment. This has enabled a material shift in the organization's sales channels, with online sales growth in 2019 reaching 23% year on year and now accounting for 14% of net sales.

These efforts have been built on top of Inditex's increasing investments in sustainability and historic core strength in supply chain segmentation. Specifically, 20% to 30% of products are fast-fashion, fast-launch products that leverage agile supply chain operations. The remainder of the product portfolio are core lines and follow a more traditional apparel supply chain production and distribution process.

In an effort to help in the COVID-19 response effort, Inditex has switched its apparel factories in Spain to making medical supplies.[12]

L'Oréal, the world's largest cosmetics company continued its upward climb to No. 10, its highest ranking to date. L'Oréal raised its ESG score to 10 by being one of only a handful of companies receiving points for recognition by both the Ethisphere Institute and Bloomberg. L'Oréal continues to show impressive capabilities such as:

- The ability to foster a customer-centric culture and become the preferred partner of customers.
- Utilizing the supply chain to enable personalized branded experiences across multiple channels.

L'Oréal also recognized the power data has in driving supply chain performance. One key element was the focus on master data management (MDM) that enables business intelligence (BI)-led supply chain decisions and supports advanced analytics and/or AI to drive supply chain performance improvements. Additionally, L'Oréal is working to accelerate product development through the use of 3D printing, digital simulation and connected assets.

Longtime retailer **Walmart** moved up three spots to No. 11, its highest ranking since 2012. The importance and relevance of Walmart's supply chain has never been higher than during the COVID-19 crisis. The business rapidly responded to the demand surge with a clear focus on supporting its community and is being rewarded with significant revenue growth. Millions in bonuses and salary advances have been given to Walmart supply chain and store staff. The company focused on ensuring shoppers, that had little or no online purchasing experience, had a clear understanding of how to use the functionality. Supply chain operations shifted to enable more rapid replenishment of critical, in-demand inventory. Across the supply chain, financial support has been provided to Walmart's small- and midsize suppliers. while resources have been dedicated to speed-up its onboarding process for its supply chain financing program.

High-tech leader **HP Inc.** comes in at No. 12. HP Inc. continues to show solid financial performance, with revenue up by 0.49% in 2019 from 2018. 2019 brought unprecedented supply chain changes, and 2020 amplified those changes and the required responses. But change brings opportunity, as HP Inc. mobilized industrial facilities worldwide to deliver 3D printed products as well as share printing solutions, creating efficiencies for its customers.

HP Inc. is also building on the new ERP foundation, moving digitally-enabled systems and ramping a more tariff-resilient supply chain. HP Inc. is becoming more customer-focused and digitally integrated, not just in supply chain, but also aligned across business units, marketing, finance, HR and IT. This foundation provides a high-quality, data-driven capability that can be leveraged to deliver value in decision making, forecasting, procurement, risk management, inventory optimization, visibility, RPA and/or ML use, and pricing analytics. Once again, HP Inc. received a perfect ESG score, by having sustainability built into the hardware, accessories, packaging and an established CE for products.

Coca-Cola moved up seven spots to No. 13 driven by strong ROPA and the third-highest peer vote among consumer product companies. Coca-Cola is developing a supply chain digital roadmap to innovate its core processes to drive improvement in agility and productivity, as well as build end-to-end transparency and traceability to best serve consumers and customers.

Coca-Cola's "World Without Waste" initiative has a renewed focus on the entire packaging life cycle from how bottles and cans are designed and made, to how they are recycled and repurposed. With a goal of 100% of packaging made recyclable by 2025, Coca-Cola is at 87% globally. The company has also opened up its bioplastics technology for its PlantBottle (the world's first, fully recyclable PET plastic bottle made partially out of plants) to all industries, including its competitors.[13] The move highlights that companies must share good ideas to protect the planet.

In response to the pandemic, Coca-Cola teams around the world are finding creative ways to use their manufacturing facilities to produce and transport needed medical supplies to the COVID-19 frontlines. Bottling plants have quickly shifted to making hand sanitizer for donation to hospitals, clinics and nursing homes. The Coca-Cola system and Coca-Cola Foundation are making contributions exceeding $100 million to support relief efforts around the world by redirecting a big part of their marketing spend to community programs, and medical supplies and equipment.

Diageo, the U.K.-based beverage leader, claimed the No. 14 spot. Diageo's commitment to standardization and simplification has enabled functional excellence to be embedded across all markets and centers of expertise. This allows consistent metrics, the ability to track and rank capabilities across the organization, performance analytics, and best-practice sharing, enabling more-efficient internal collaboration.

During the past two years, Diageo has made considerable investment in transforming its procurement organization with a focus on simplification, supplier partnership and business engagement. Deploying best-in-class digital capabilities is allowing data-driven analytics. A robust supplier relationship management framework is enabling end-to-end supply chain engagement on sustainability and collaboration across the business for long-term, strategic-value creation.

Lenovo rejoins the list, leaping nineteen spots to No. 15. Lenovo reported record revenue in 2019, which is a four-year growth trend. Lenovo has a unique heritage from the integration of up to nine companies and the cultural combination of East and West. This diversity has been embraced and has fueled a transformation journey for more than 20 years. Lenovo has developed a wide portfolio of products, but more importantly, in the move to customer-centricity it has been able to harvest the customer insights that drive customer-valued innovation.

Advanced supply chains have learned to build a bridge which involves using data to derive insights and to act on the insights to drive value. Lenovo has done this on multiple fronts. The innovation foundation that is used includes technologies such as predictive analytics, AI, blockchain and autonomous things. Lenovo demonstrates leadership in sustainability, the CE, and diversity and inclusion, and raised its ESG score 4 points to a perfect 10.

Rounding Out the List: No. 16 Through No. 25

Footwear and apparel leader **Nike** lands at No. 16. Nike's organizational fortitude in the face of major disruption shone through, with revenue rising five percent on a reported basis and digital sales up 36 percent versus the prior year for its fiscal third quarter ending 29 February 2020. Adaptability to change is a key capability at Nike. With people confined at home beginning in January, Nike was able to leverage its digital app ecosystem and its expert trainer network to inspire and support consumers across China to stay active and connected while at home. This resulted in a 3Q increase in weekly users of 80% compared to the beginning of the quarter. This engagement translated into strong engagement with the Nike commerce app and contributed to more than a 30% increase in the digital business in China.

Life sciences company **AbbVie** made its first entry in the Top 25 landing at No. 17. AbbVie has had two unique supply chain opportunities in its short lifetime. First, when spun-off from Abbott in 2014, it was able to design its supply chain from the "ground up" — implementing best practices from its parent company, but also building new ones, where it made sense. Second, the majority of its revenue is driven by one product — HUMIRA (used to treat rheumatoid arthritis). This has allowed AbbVie to focus its supply chain efforts and maximize efficiencies.

With AbbVie's acquisition of Allergan, all this is set to change. No longer will AbbVie be just a biologics company — Allergan brings with it a broad portfolio that includes eye care, aesthetics and central nervous system (CNS) products. As a result, AbbVie will have to build supply chain processes and teams that excel in different channels and manage product life cycles effectively.

Luxury auto manufacturer **BMW** climbed seven spots to No. 18., in part, due to back-to-back perfect ESG scores. BMW recognizes the supply chain as a critical enabler of the company's product differentiation strategy. Supply chain flexibility enables BMW to offer customers choice and respond to changing market situations and regional demand. More than 20,000 interior variants are possible with the BMW 3 Series. Supply chain flexibility is enabled by the extended production network, comprising 31 locations in 15 countries with 20 sites owned by BMW.

It has shipped over 140 thousand electric vehicles on its path toward company digitalization and vehicle electrification. To ensure utilization, it is integrating the production of all-electric and plug-in hybrid vehicles into the existing manufacturing system. Its workforce investments include hiring in future-oriented fields, such as AI, and smart production and logistics. New training profiles at its German plant locations include IT application development, IT system integration and electronics for automation technology.

Beverage creator **Starbucks** lands at No. 19. Starbucks has been a longtime innovator and leader in the integration of digital and physical retail, deploying concepts such as electronic payments, mobile apps, pick-up only stores and leveraging third-party delivery networks, all in an effort to improve responsiveness. The business is increasingly using China as a test-bed for new emerging consumer-driven efforts. For example, the well-established, last-mile delivery partnership with Alibaba's Ele.me has been used as a model for the deployment of online order delivery in the U.S., starting in 2019. The timing of these efforts alongside the agile nature of its supply chain operations have proved fortunate, positioning Starbucks to weather the COVID-19 storm in 2020, and accelerate its shift toward increased digital sales moving forward.

Additional efforts are also being made to accelerate the sustainability of Starbucks operations, including testing of reusable cups at specific airport locations, leveraging blockchain technology to track coffee from the bean grower to consumers' cups, and the expansion of plant-based options on its menu.

Swedish fashion retailer, **H&M** lands at No. 20. H&M continues to maintain its leadership position in the area of sustainability where 97% of the group's cotton used in production is recycled or sustainably sourced. As part of these efforts, it is opening up its global supply chain operations through a newly established B2B service called Treadler. Through Treadler, H&M can offer access to its global supply chain, as a service to external companies. This enables companies to benefit from H&M's expertise, long-term supplier partnerships and strategic sustainability work. This allows smaller brands that use the service to leverage H&M and its suppliers for everything from product development and sourcing through to production and logistics.

These same extensive supply chain resources offered through Treadler are now also being pivoted to support the global response to COVID-19. Since March 22, instead of clothing, many of H&M's key suppliers are now manufacturing large quantities of PPE, which are donated to hospitals and healthcare workers around the world.

British American Tobacco (BAT) continued its upward journey, landing at No. 21. BAT's portfolio ranges from traditional cigarette brands to modern low-tar and no-tar oral products, tobacco heating products and vapor products. The innovation in products requires major investments in new technologies.

BAT has been identified as a global leader for engaging with its suppliers on climate change, being awarded a position on the Supplier Engagement Leaderboard compiled by global environmental impact nonprofit organization CDP, and is the only tobacco company listed in the Dow Jones Sustainability Index (DJSI).[14]

3M, a company with a longtime legacy of leadership in innovation, comes in at No. 22. 3M has completed its major ERP implementation, and in 2019 it consolidated the business from five business groups to four, creating internal efficiencies. It is implementing a new global operating model — 3M's business group-led operating model. With that, it is giving each of the business segments the full commercial responsibility of strategy, portfolio optimization and resource prioritization. It is also consolidating its end-to-end supply chain, including manufacturing, under the Enterprise Operations organization, to drive organizational efficiencies across the business.[15]

3M showed its supply chain resiliency as the primary U.S. producer of N95 masks. The company doubled production to some 100 million masks between January and April of this year, after cases of the COVID-19 began to proliferate in China.[16] In 2019, 3M listed its priorities as portfolio transformation, innovation, and people and culture as key initiatives. The company is putting numerous efforts in place, including organizational changes and initiatives in talent, innovation, transformation and product portfolio.

Another newcomer to this year's list, **Reckitt Benckiser,** lands at No. 23. The company achieved significant improvement in its packaging, talent attraction and retention, and product quality and recall management scores. Notable progress was made across SCM, human rights and risk management.[17]

Reckitt Benckiser (RB) mobilized £32 million as part of its RB Fight for Access Fund with immediate focus to address the stress faced by its consumers and communities where it operates to break the chain of infection of COVID-19.

Life science company **Biogen** makes its Top 25 debut at No. 24. Biogen has long prided itself in its exceptional service levels to patients, primarily in large molecule products. Biogen enables this through strong supply chain leadership and product technology acumen. Unlike many life science supply chains that see product portfolios that continue to diversify, Biogen focuses on biologic medicines and biosimilars, allowing it to tailor supply chains to specific needs of these products.

Realizing an opportunity to leverage the strength of the healthcare ecosystem, Biogen is pursuing digital technology as a means of creating external connections. At a time when most digital initiatives in the industry are focused on products, Biogen is instead looking to create value by enabling better information flow.

Kimberly-Clark secures No. 25. Kimberly-Clark believes that long-term strategic supplier relationships are key to driving innovative solutions that meet its customer and consumer needs. An example of this is how it worked with its eucalyptus pulp supplier, Fibria, to support and collaborate with smallholders across its value chain to address any challenges to obtaining Forest Stewardship Council (FSC) certification. If smallholders are FSC-certified, their land is a renewable, sustainable source of direct income.

Through the COVID-19 crisis, while Kimberly-Clark worked to get toilet paper back in stock in the U.S., it implemented #ShareASquare that encourages those with toilet paper to spare to those who need it. The company asked consumers to show how they shared via social media and Kimberly-Clark would donate $1 to United Way for each post that featured #ShareASquare.[18] Additionally, Kimberly-Clark has committed to donations totaling more than $8 million to assist with the COVID-19 response and recovery efforts around the world.

Honorable Mentions

Companies that demonstrated strong leadership in demand-driven principles but did not make the list include:

General Mills

General Mills is accelerating digital transformation efforts across its entire supply chain, differentiating its capabilities with a focus on segmentation, integrated planning, network optimization and analytics.

General Mills set a goal of 100% renewable electricity by 2030, as part of the RE100 global corporate initiative. To achieve this, the company is investing in renewable efforts to support the company's environmental objective. Examples include large-scale wind farms that will produce renewable credits (RECs) and anaerobic digestion that captures and uses methane from waste to generate electricity.[19]

Danone

Danone is heavily committed to sustainability and is recognized as a global environmental leader, becoming one of the six companies with a "AAA" score by CDP worldwide.[20] Additionally, Danone has focused on gender parity in management roles. This was achieved in 2019, with females representing 51% of managers, directors and executives. Danone has provided financial support of over £300 million, including extended payment terms and credits to farmers, suppliers and smaller customers in its global ecosystem.

CVS Health

In the face of potential industry disruption from the likes of Amazon, CVS Health is expanding its supply chain capabilities with a clear emphasis on the development of last-mile operations. It has established a paid membership service called CarePass that provides subscribers with free one- to two-day delivery across prescriptions and other eligible purchases. However, it is in the area of drone delivery that it is taking real industry leadership via a partnership with UPS. Its first drone delivery of a medical prescription occurred in North Carolina in November 2019. These drone delivery efforts have recently been expanded and now include a Florida retirement community of more than 135,000 residents.

Finally, we would like to highlight some of the companies that are not on the global Top 25 list but received higher than average peer votes from the Supply Chain Top 25 peer opinion poll. These crowd favorites include Toyota, Adidas, Heineken, Costco, Target and Dell Technologies.

All of these companies exhibit leadership characteristics and have compelling lessons for the broader supply chain community. We look forward to sharing lessons from them and many others in the year ahead.

Supply Chain Top 25 Methodology

The ranking comprises two main components — business performance and opinion. Business performance, in the form of public financial and ESG data, provides a view into how companies have performed in the past. The opinion component offers an eye to future potential and reflects leadership in the supply chain community. These two components are combined into a total composite score.

We derive a master list of companies from a combination of the Fortune Global 500 and the Forbes Global 2000. In an effort to maintain the list of companies evaluated at a manageable level, we apply a general annual revenue threshold of $12 billion.

We then pare the combined list down to the manufacturing, retail and distribution sectors, thus eliminating certain industries, such as financial services and insurance (see Table 2 for a full list of excluded industries).

Table 2. Industries Not Included in the Supply Chain Top 25

Airlines	Information technology/ computer services	Shipping
Banks	Insurance	Services
Crude oil production	Mail, package and frieght delivery	Shipbuilding
Diversified financials	Metals	Software development
Electronics manufacturing services	Mining	Telecommunications
Energy	Petroleum refining	Temporary help
Engineering/construction	Pipelines	Trading
Entertainment	Railroads	Utilities
Healthcare: Insurance, managed care, services, providers	Real estate	

Source: Gartner

For the 2020 ranking, we investigated a number of possible changes to the methodology. The goal was to have the methodology keep pace with the changes that we see happening in modern supply chains. These include aligning the supply chain with the assets they control, a continued emphasis on ESG and recognizing the changing role of inventory. Our evaluations included quantitative exercises, such as running potential changes against datasets from previous years. We also solicitated qualitative feedback from a cross-section of the community, including representatives from more than 100 individual companies and a formal feedback session with Gartner's Supply Chain Executive Advisory Board, comprised of global CSCOs from leading companies.

This feedback and dataset testing resulted in changes to the 2020 methodology (see "Methodology Changes for the 2020 Gartner Supply Chain Top 25"). As shown in Table 3, the Top 25 ranking is based on a combination of financial performance and opinion data. The financials give us an objective basis on top of which we place the community peer vote component.

Table 3. The Supply Chain Top 25 Methodology

Category	2019 Measure	Weighting	2020 Measure	Weighting
Business Data (50%)	Return-on-assets (ROA)	20%	Return-on-physical-assets (ROPA)	20%
	Inventory turns	10%	Inventory turns	5%
	Revenue growth	10%	Revenue growth	10%
	CSR	10%	Environment, social, governance (ESG)	15%
Community Opinion (50%)	Analyst vote	25%	Analyst vote	25%
	Peer vote	25%	Peer vote	25%

Source: Gartner

The current quantitative components of the Supply Chain Top 25 scoring system use publicly available data to calculate financial performance scores. The ESG component also uses third-party data as a proxy for assessing each company's commitment to, and proficiency in, running ESG-responsible supply chains.

The following business data financial and ESG metrics are used in the ranking:

- ROPA — Operating income/Net property, plant, equipment and year-end inventory
- Inventory turns — Cost of goods sold/quarterly average inventory
- Revenue growth — Change in revenue from prior year
- ESG — Index of third-party ESG measures

ROPA gives a view into the productivity of the assets managed by the supply chain and inventory provides a proxy for efficiency. Revenue growth, while clearly reflecting a myriad of market and organizational factors, offers clues into how the supply chain enables innovation.

We use a three-year weighted average for the ROPA and revenue growth metrics, and a one-year quarterly average for inventory. The yearly weightings are as follows: 50% for 2019, 30% for 2018, and 20% for 2017.

The use of three-year averages is in place to accomplish two goals. The first is to smooth the spikes and valleys in annual metrics, which often aren't truly reflective of supply chain health, and that often result from events such as acquisitions or divestitures. It also accomplishes a second, equally important goal: To better capture the lag between when a supply chain initiative is put in place (e.g., a network redesign or a new demand planning and forecasting system) and when the impact can be expected to show up in financial statement metrics, such as ROPA and revenue growth.

On the other hand, inventory is a metric that's much closer to supply chain activity and we expect it to reflect initiatives within the same year. The reason we use a quarterly average for inventory is to get a better picture of actual inventory holdings throughout the year, rather than the snapshot, end-of-year view provided on the balance sheet in a company's annual report.

The primary source for all publicly available financial data is S&P's Capital IQ (CapIQ) database. In some instances, CapIQ financial reports may include standardizations to ensure a consistent reporting methodology across companies.

We designed a scoring system for ESG based on our research, input from third-party experts in ESG, a cross-section of supply chain community members and our broader research organization.

Each company has the opportunity to achieve up to 10 points for evidence of its ESG commitment, transparency and performance. The broader "business data" category reflects the more recent inclusion of the nonfinancial data captured in the ESG score.

Beginning in 2020, this component of the methodology will be referred to as "ESG" (previously CSR) and the weighting is increased from 10% to 15%, and includes the following two new measures of performance:

- Ethical companies list (2 points)
- Gender equality index (2 points)

The ESG component includes two third-party data sources — The Ethisphere Institute and Bloomberg. These additional measures are reflected within the performance portion of the ESG methodology and provide additional ways to garner the six ESG performance points.

Opinion Component

We find that companies that continually secure spots on the Supply Chain Top 25 have successfully shifted from the traditional, disconnected approach to managing supply, demand and product to an integrated approach to coordinating plan, source, make and deliver functions across the end-to-end supply chain (see "Gartner's Demand-Driven Model for Supply Chain Excellence"). These leading companies are frequently identified as being a "partner of choice" and often a target for collaboration activities within their ecosystem.

The opinion component of the ranking is designed to provide a forward-looking view that reflects the progress that companies are making and the extent to which they demonstrate leadership through visibility in the supply chain community. It's made up of two components, each of which is equally weighted — a Gartner analyst expert panel and a peer panel.

The goal of the peer panel is to draw on the extensive knowledge of the professionals who, as customers and/or suppliers, interact and have direct experience with the companies being ranked. Any supply chain professional is eligible to be on the panel, and only one panelist per company is accepted. Excluded from the panel are consultants, technology vendors and people who don't work in supply chain roles (e.g., those in public relations, marketing or finance).

For this year's peer panel, 151 supply chain professionals completed the voting process. Participants came from the most senior levels of the supply chain organization across a broad range of industries. There were 44 Gartner panelists across industry and functional specialties, each of whom drew from their primary field research and continuous study of companies in their coverage area.

Organizations must surpass a base threshold of votes from both panels to be assigned a numerical rank. For example, a company that had a composite score fall within the Supply Chain Top 25, based solely on its financial metrics, would not be included in the ranking.

The following tables provide a breakdown of the peer vote on the dimensions of region, industry, revenue and level (see Tables 4, 5, 6 and 7):

Table 4. 2020 Peer Opinion Panel Composition: Region

Region	%
Americas	48%
APAC	19%
EMEA	33%

Source: Gartner

Table 5. 2020 Peer Opinion Panel Composition: Industry

Industry	%
Academic	14%
Auto	6%
Chemical	8%
CPG	30%
Electronics	13%
Industrial	10%
Life Sciences	8%
Miscellaneous	5%
Retail	7%

Source: Gartner

Table 6. 2020 Peer Opinion Panel Composition: Revenue

Revenue	%
Less than or equal to $999 million	19%
$1 billion to $4.9 billion	23%
$5 billion to $9.9 billion	10%
$10 billion to $24.9 billion	22%
$25 billion to $49.9 billion	13%
More than $50 billion	14%

Source: Gartner

Table 7. 2020 Peer Opinion Panel Composition: Level

Level	%
Academic	15%
Senior director, director or manager	43%
Vice president	24%
SVP, EVP or C-suite	19%

Source: Gartner

Polling Procedure

Peer panel polling was conducted in March of 2020, via a web-based, structured voting process similar to previous years. Panelists are taken through a six-page system to get to their final selection of leaders that are the closest to the demand-driven ideal, which is detailed in the instructions on the voting website for the convenience of the voters. Again, we offered voters the option of sorting the list of companies in our study, either alphabetically or by industry grouping, to aid in their company selection process.

We continued including consideration of ESG practices in this year's opinion poll voting criteria. We specify that voters consider each company's commitment to running a supply chain that addresses social, environmental, ethical human rights and consumer concerns in its operations and core strategy.

The following is a breakdown of the voting system:

- The first page provides instructions and a description of the demand-driven ideal.
- The second page confirms demographic information.
- The third page allows voters to view the company list, alphabetically or by industry.
- The fourth page provides voters with a complete list of the companies to be considered. We ask them to choose 25 to 50 that, in their opinion, most closely fit the demand-driven ideal.
- The fifth page asks the voters to force-rank the companies from No. 1 to No. 25, with No. 1 being the company most closely fitting the ideal listed.
- The last page allows voters to review their final selections and submit their rankings.

Individual votes are tallied across the entire panel, with 25 points earned for a No. 1 ranking, 24 points for a No. 2 ranking and so on. The Gartner analyst panel and the peer panel use the exact same polling procedure.

By definition, each peer voter's expertise is deep in some areas and limited in others. Despite that, peer voters aren't expected to conduct external research to place their votes. The polling system is designed to accommodate differences in knowledge, relying on what author James Surowiecki calls, "The Wisdom of Crowds" to provide the mechanism that taps into each person's core kernel of knowledge and aggregates it into a larger whole.

Composite Score

All this information — the four business data points and two opinion votes — is normalized onto a 10-point scale and then aggregated, using the aforementioned weighting, into a total composite score. The composite scores are then sorted in descending order to arrive at the final Supply Chain Top 25 ranking.

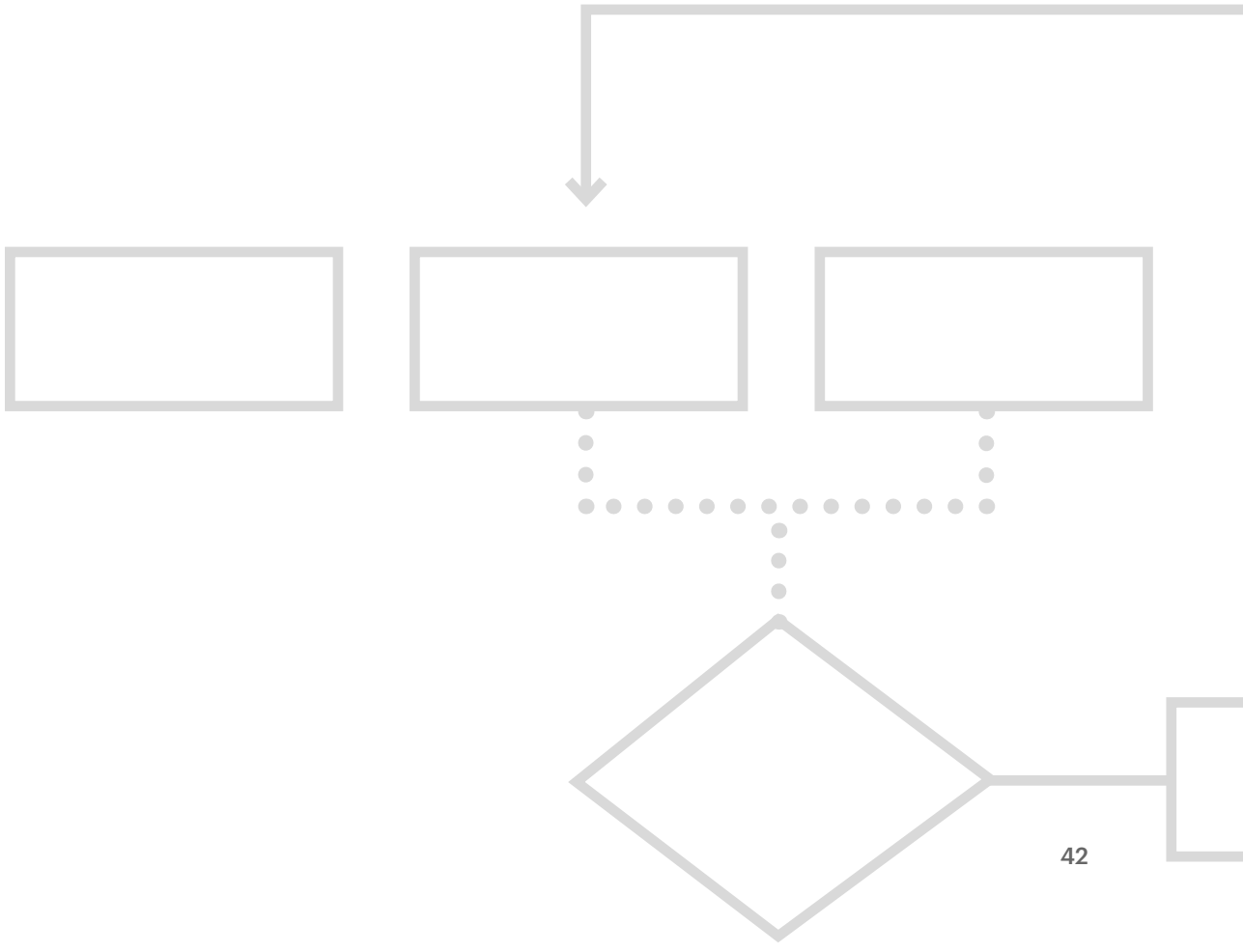
Looking Ahead

As we look forward to the future of the Supply Chain Top 25, we are excited to share the latest lessons from leaders in the supply chain community and to foster a discussion with you on the definition of leadership.

The Healthcare Supply Chain Top 25 for 2020 will publish in the second half of 2020, among a steady cadence of additional publications that offer various analytical lenses on the full 2020 global rankings. These include industry cuts that examine how the companies in a particular industry stack-up against each other and what the industry can learn from them, as well as regional cuts for Asia/Pacific and Europe, providing the same information for companies headquartered in each region. These cuts will be published throughout the remainder of the year. We will also publish a results guide listing the top ranked supply chains from each industry, as well as a summary report with links to all 2020 Supply Chain Top 25 research notes, for ease of reference.

As always, we'll continue to field feedback and investigate new approaches for measuring supply chain leadership. Of note, we have already identified one change for 2021. To reflect the continued importance of ESG, a company must have an ESG score greater than zero in order to be included in the population and eligible for ranking.

Every year, we see leading companies experiment and advance their supply chain capabilities, leaving the rest of the pack further behind. As Gartner's supply chain research organization, we remain committed to providing a platform for informed and provocative debate about supply chain leadership. In today's uncertain and complex world, our Supply Chain Top 25 research is an opportunity to learn how the most advanced companies adapt and thrive to stay ahead of the competition. We look forward to leveraging this research to share the lessons, best practices and characteristics of leaders to inspire and challenge the entire supply chain community to new levels of performance and contribution.



Gartner Recommended Reading

Some documents may not be available as part of your current Gartner subscription.

"The Gartner Supply Chain Top 25 for 2019"

"Methodology Changes for the 2020 Gartner Supply Chain Top 25"

"What Western Businesses Can Learn as China Comes Out of COVID-19 Lockdown"

"Future of Supply Chain: Reshaping the Profession"

"2019 Gartner Supply Chain Top 25: Retail"

"Supply Chain 2029: Disruptions Impacting Future Innovation"

"Supply Chain Brief: Compare the Progress of Your Digital Supply Chain Roadmap"

"Employ Digital Technology to Enable a Circular Economy"

"Life Sciences Supply Chainnovator Finalists 2020: Tackling Stock-Outs, Returns and Employee Innovation"

"The Healthcare Supply Chain Top 25 for 2019"

"Supply Chain Transformation Guide"

"Ignition Guide to Creating a Digital Supply Chain Roadmap"

Evidence

1 "Winners of 2019 FICO Decisions Awards Announced! Companies Celebrated for Analytic Excellence." FICO.com.

2 "Satellites Are Helping to Track Food Supplies in the Coronavirus Era," Transport Topics.

3 "Colgate-Palmolive Receives 2019 Leadership Award From U.S. Green Building Council," Colgate-Pamolive.

4 "Colgate to Open Source Recyclable Toothpaste Tube Tech," Global Cosmetics News.

5 "5 Impactful Ways Johnson & Johnson Is Helping in the Fight Against Covid-19," Johnson & Johnson.

6 "What Is Ecostruxure From Schneider Electric?" BPX Electro Mechanical

7 "The Growing Personalized Nutrition Market Has a Big New Contender: Nestlé," Forbes.

8 "Nestle Supply Chain Remains 'Robust,'" Food Business News.

9 "Digimarc Barcode Scores High on Recycling," Digimarc.

10 "PepsiCo's U.S. Operations Will Be Powered by 100% Renewable Electricity This Year," Fast Company.

11 "Intel Corp (INTC) Q1 2020 Earnings Call Transcript," Motley Fool.

12 "Spain's Coronavirus Crisis Stalls Global Fashion Giant Inditex," ETRetail.com

13 "Introducing a World-First: A Coke Bottle Made With Plastic From the Sea," Coca-Cola.

14 "British American Tobacco Recognized as Global Leader for Engaging Its Supply Chain on Climate Change," British American Tobacco.

15 "3M to Cut 1,500 Jobs as 2019 Sales Fall 1.9%," Industrial Distribution.

16 "3M, Under Attack From White House, Pushes Back," The Wall Street Journal.

17 "RB Rejoins Dow Jones Sustainability World Index," Reckitt Benckiser.

18 "Add to Subtract: How Kimberly-Clark Is Boosting Sustainability With a Simple Addition to Product Packaging," 3BL Media.

19 "General Mills Commits to 100% Renewable Electricity Globally by 2030," CSRwire.

20 "Danone Recognized as a Global Environmental Leader, Becoming One of the 6 Companies With 'AAA' Score by CDP Worldwide," Danone.

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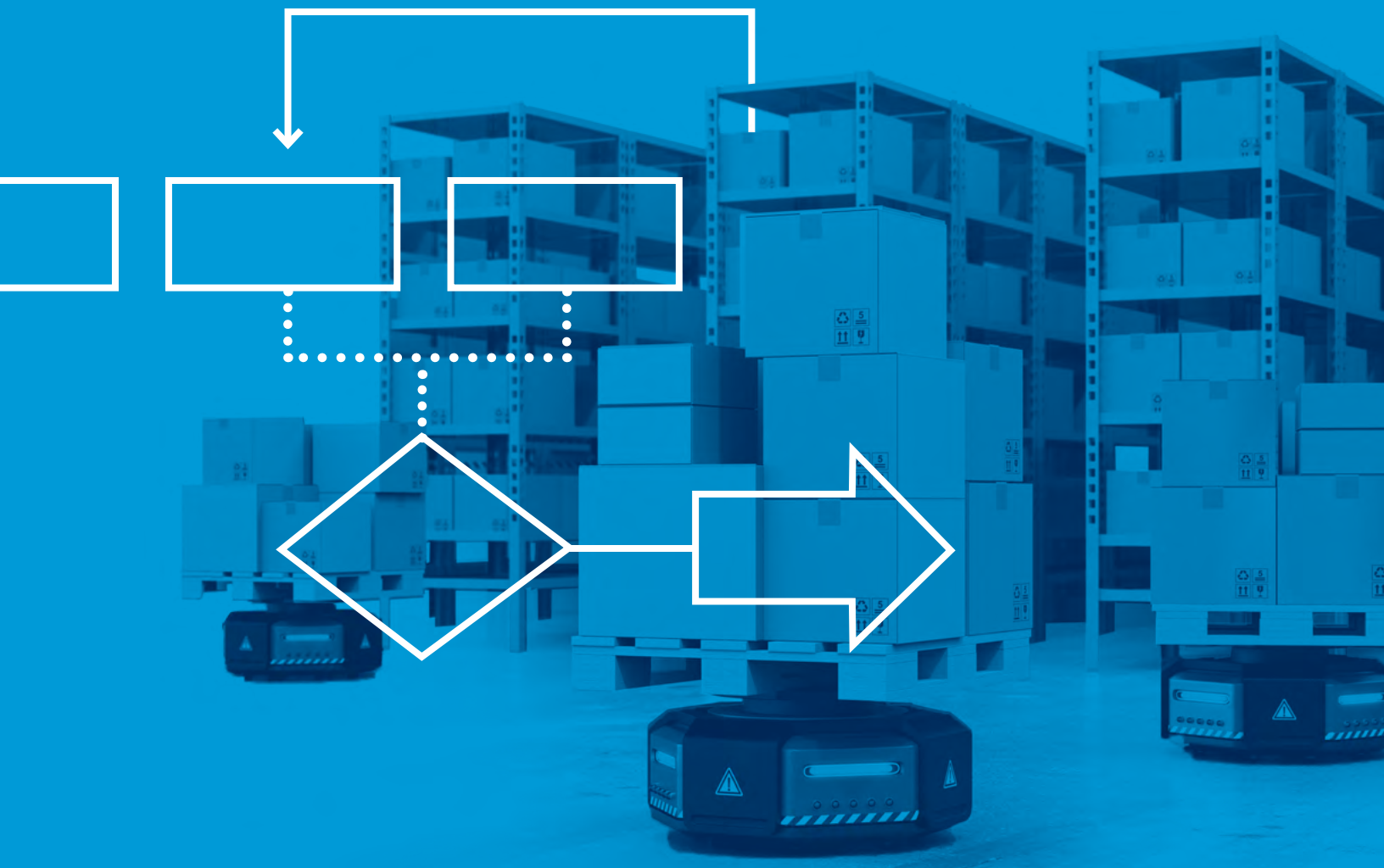

The journey of bottled water

ANALYSIS

Global supply chains have given consumers in developed countries ever cheaper goods, but Ashley Potter talks to Mark Johnson about the journey of bottled water that has given us a more expensive product

It sounds easy doesn't it? Put some water in a bottle and sell it.

But a look at the supply chain of number one US importer Fiji Water shows it is not nearly that simple and involves 20,978 miles of travel before it finds its way into the shops of downtown New York.

It involves shipping material across two continents and between four countries before being exported to the US where Fiji Water has two per cent of a bottled water market worth an estimated $10.6billion a year.

It might be convenient to pop into a shop and buy some water, but it is far from convenient to organise the manufacture of the product and shipping of what makes up the plastic bottle.

Of course the major cost is making the plastic bottle to contain the water. According to charity The Water Project it takes three litres of water to make the packaging for one litre of bottled water, while it estimates that 1.5 million barrels of oil a year are needed to produce the plastic for the US market.

Mark Johnson, Associate Professor of Operations Management at Warwick Business School, researches supply chains and believes the case of bottled water is an example of how the globalisation of manufacturing leads to a fairly ridiculous and lengthy supply chain.

"There is a large distance travelled in the materials needed to make the bottle," says Johnson. "That brings into question the environmental impact of our need for bottled water when in the US and other developed countries tap water is perfectly good enough to drink. In fact, in a taste test conducted by *The Guardian* of 10 tap waters and bottled waters, Severn Water's tap water came out on top."

Fiji Water source the plastic blanks for their plastic bottles from Allentown in Pennsylvania, US. They are shipped 7,895 miles to Rakiraki on the Fijian island of Viti Levu where the spring water originates. The plastic bottle tops come from Taichung City in Taiwan, chugging 4,815 miles across the North Pacific Ocean to Fiji. The paper labels are made in Wellington, New Zealand, before travelling the relatively short distance of 1,666 miles.

At its factory on Viti Levu, 400 workers manufacture the bottled water before the final leg of the journey, 6,602 miles to Plano in Texas from where it is distributed across the country.

A one litre bottle of Fiji Water can vary in price, between $2–$3, but with Johnson putting manufacturing costs at 22 cents it is a healthy return.

"It makes it more expensive than a litre of unleaded petrol," says Johnson. "In the UK, tap water costs 0.151p a litre. It is expensive, it travels a lot of miles, and there is a lot of waste. Polyethylene terephthalate (PET) bottles can be recycled, but only about 40 per cent of them are."

Fiji Water is just one brand in a competitive bottled water market and, though there may be concerns about the environmental impact of a product that developed countries don't actually need, demand is growing.

The International Bottled Water Association reported a rise in consumption of bottled water in the US in 2012 by 6.2 per cent to 9.67 billion gallons.

Johnson adds: "It may seem like a waste of resources, but there is a demand for bottled water and it is at least providing employment in Fiji and revenue throughout the supply chain. But we must be aware of the cost that the convenience of bottled water has on the environment and our diminishing resources." ■

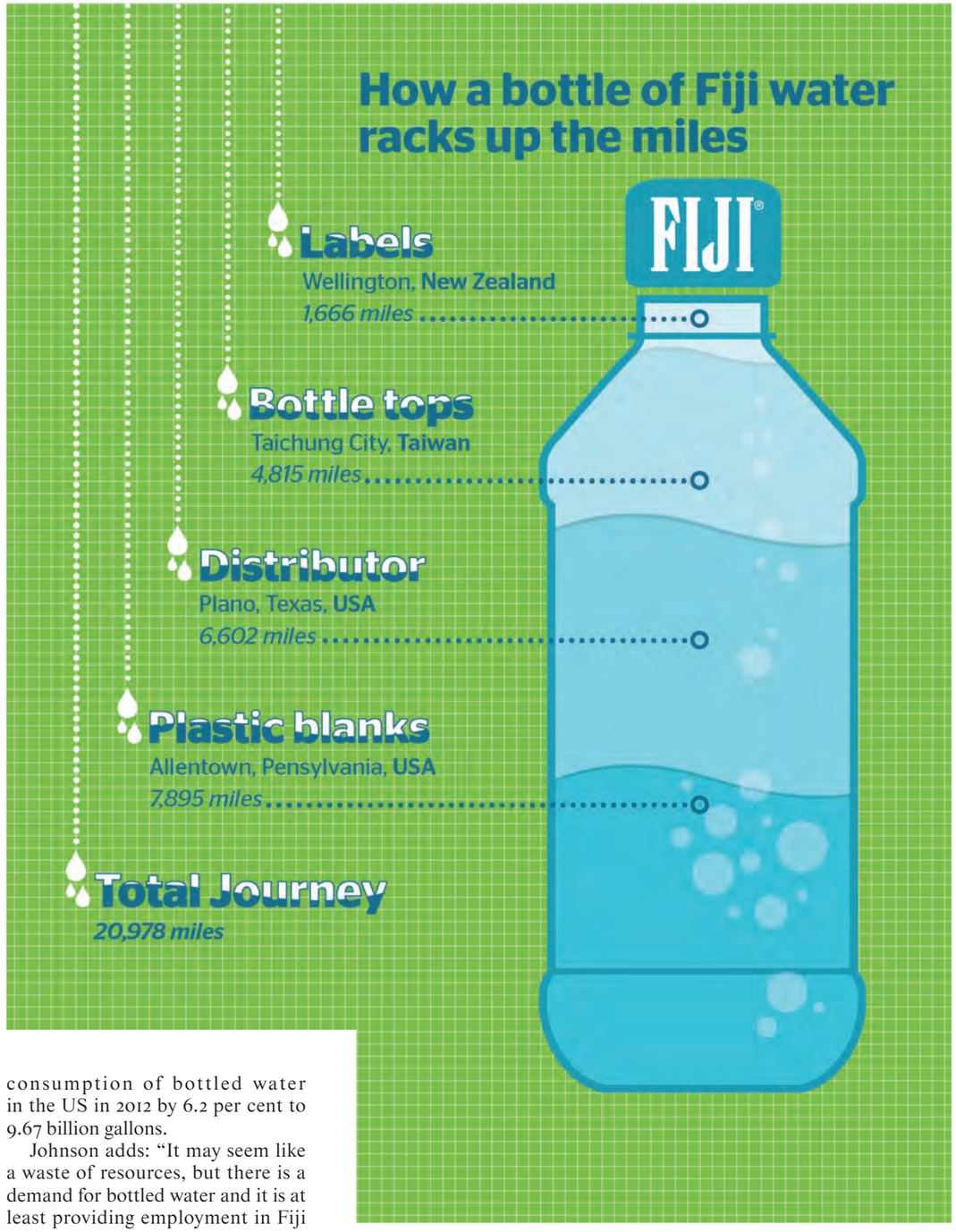

Illustration: Rebecca Cutts

Watch Mark Johnson's short film 'Supply Chains' at wbs.ac.uk/go/supplychains

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A supply chain disruption recovery strategy considering product change under COVID-19

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ABSTRACT

A recent global outbreak of Corona Virus Disease 2019 (COVID-19) has led to massive supply chain disruption, resulting in difficulties for manufacturers on recovering their supply chains in a short term. This paper presents a supply chain disruption recovery strategy with the motivation of changing the original product type to cope with that. In order to maximize the total profit from product changes, a mixed integer linear programming (MILP) model is developed with combining emergency procurement on the supply side and product changes by the manufacturer as well as backorder price compensation on the demand side. The model uses a heuristic algorithm based on ILOG CPLEX toolbox. Experimental results show that the proposed disruption recovery strategy can effectively reduce the profit loss of manufacturer due to late delivery and order cancellation. It is observed that the impact of supply chain disruptions is reduced. The proposed model can offer a potentially useful tool to help the manufacturers decide on the optimal recovery strategy whenever the supply chain system experiences a sudden massive disruption.

1. Introduction

Supply chain refers to the entire process of making and selling commercial goods, including every stage from the supply of materials and the manufacture of the goods through to their distribution and sale [1,2]. Over the past few decades, large-scale disruptions of supply chain have been caused by natural and man-made disasters, such as 2004 Indian Ocean earthquake, 2008 U.S. subprime mortgage crisis, 2011 Japan tsunami and so on [3]. With specialization and concentration in manufacturing industry, disruptions at one or a few entities can affect almost all ones in supply chain [4]. Once such disruptions occur, the whole supply chain has to face a lot of problems, such as supply disruption [5], production disturbance [6] or demand change [7]. Therefore, it is very important to design resilient supply chains so as to cope with different disruptive events effectively [8,9].

Supply chain resilience management usually starts with risk prediction or risk identification, that is, to predict possible risks and to develop different strategies for identifiable risks [10]. This approach can effectively deal with those disruptions that have occurred before and can be expected. For unexpected disruptions that are difficult to predict, an important issue for building resilience of supply chain is to develop the effective recovery strategies so that the system can respond and recover quickly from the disruptions [11,12]. In the case of the Volkswagen Group, for example, the COVID-19 pandemic that outbreak from December 2019 has affected the supply of chips related to ESP (Electronic Stability Program System) and ECU (Electronic Control Unit). During COVID-19 pandemic, many chip suppliers have been reducing their production capacity or shutting down their factories, which would lead to the disruption risk of supply chain in the production of some Volkswagen vehicles. According to statistics, 938 of Fortune's 1000 largest companies suffered the serious influences of raw material supply and production due to the disruptions in global supply chains caused by this epidemic outbreak[1] . Queiroz et al. [13] systematically analyzed the impact of the COVID-19 pandemic upon supply chain through a structured literature review. The large-scale disruptions of supply chain system could result in such high economic losses due to the following three distinctive characteristics: 1) the unpredictability of the disruption over time and its magnitude; 2) the simultaneous spread of the disruption through both the system (i.e., ripple effect) and the population (i.e., pandemic spread); 3) the partial or total simultaneous disruption of supply, production, demand, and logistics infrastructure [14,15]. Compared with previous epidemics (e.g., SARS, H1N1), COVID-19

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[1] https://fortune.com/2020/02/21/fortune-1000-coronavirus-china-supply-chain-impact/

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would last longer and spread more widely, which causes more severe disruptions and increase the recovery difficulty for supply chain greatly [16,17].

Ivanov et al. [18] categorized the schemes of dealing with the disruption risk of supply chain as proactive and reactive. The former emphasized identifying and anticipating the existing vulnerabilities and the potential disruptions of supply chain [19–21], while the latter focused on developing the recovery strategies for different disruptions [22–24]. However, the existing proactive or reactive strategies cannot cope with the prolonged disruption caused by COVID-19 effectively. For one thing, the disruption degree of supply chain could hardly be identified in the proactive context. For other, the supply capacity could not be recovered quickly in the context of reactive strategies due to such sudden outbreak cause a large-scale disruption of the original or alternate suppliers for a longer period. Therefore, a new recovery strategy will be developed with consideration of product change [25,26] to mitigate the disruption impact of supply chain under the COVID-19 pandemic in this paper. A mixed integer programming model with minimizing the total cost of recovering from the disruption of supply chain will be developed. From the numerical results, we will identify how the cost factors, that is, product change duration, new supplier selection and allocation, and customer sensitivity, play the different roles in the product change scheme.

The remainder of the paper is organized as follows. Section 2 provides an overview on relevant literature. The problem definition, the symbolic representation and the underlying assumptions are given in Section 3. Section 4 presents the mathematical model and its solution method. Numerical experiments and the discussion of results are given in Section 5. Section 6 gives management insights and the final section summarizes this paper and provides a perspective for future work.

2. Literature review

Disruptions can occur in any part of supply chain, including the upstream supply side, the intermediate manufacture processes, and the downstream demand side. As an interdependent and interconnected whole, local disruption can propagate through supply chain and wreak havoc on the entire supply chain [27]. Ivanov et al. [28] referred to this phenomenon as a ripple effect. Unlike the bullwhip effect triggered by small demand vulnerability [29], the disruption in the ripple effect could either originate at the supply side and propagate positively along the logistics direction, or originate at the demand side and propagate negatively upstream, which would affect more enterprises in the supply chain [30]. Li et al. [31] distinguished the forward and backward propagation of disruptions and gave a detailed analysis on the factors affecting the propagation of disruptions. Zhang et al. [32] explored the propagation of disruption risk in the automotive supply chain by surveying 31 Chinese automotive-related firms.

In the work of Ivanov et al. [18], two major categories of strategies, that is, proactive and reactive, were used to deal with the disruption risk of supply chain. Proactive strategies are referred to those that are in action before a disruption occurs. Knemeyer et al. [33] developed a process for proactive planning of catastrophic risk events by integrating the different strategy streams of risk management. In order to reduce the generated disruption costs by purchasing raw materials in advance, Pal et al. [34] proposed a three-level supply chain model based on an economic production quantity inventory model, which was termed as EPQ in [35]. Torabi et al. [36] presented a bi-objective hybrid two-stage stochastic planning model to reduce the impact of supply-side disruptions with consideration of using alternate suppliers or developing a supplier continuity plan. Islam et al. [21] presented an inventory model considering random inventory, reliability of suppliers, and delivery capacity to optimize the inventory plans of manufacturers. Although system resilience can be enhanced by building redundancy or flexibility, such built-in resilience increases costs, and these proactive mitigation strategies may not be appropriate for dealing with unexpected supply chain disruptions [37].

The reactive strategies are more effective to enable supply chain to quickly return to the normal state after a disruption happens to the system [38]. Xia et al. [39] developed a two-stage generic production and inventory disruption recovery model, which take into account the cost of deviation from the normal schedule after recovery, and introduced the concept of disruption recovery time window. Hishamuddin et al. [40] extended the model of Xia et al. [39] and proposed an economic batch model based on disruption recovery method by determining the optimal manufacturing batch size and the optimal recovery duration for a production run in the recovery time window to minimize the expected total cost of ownership. Paul et al. [41] proposed the concepts of backorders and lost sales respectively to develop a two-stage supplier-manufacturer supply chain recovery model under disruption risk. Kaur et al. [42] presented an independent production and procurement integration model, where both the changes of market demand and the uncertainty of manufacturers, suppliers, and transporters were considered. Malik et al. [43] developed a disruption recovery model for a multi-product, single-stage manufacture system in order to obtain the optimal procurement lot size for multiple materials under the budget and storage space constraints in the given recovery time window. Ivanov et al. [44] observed that disruptions in production capacity create a risk of product shortages, and developed a coordinated contingency policy for production order in the supply chain during and after disruptions. Gupta et al. [45] developed an analytical game-theoretic model to cope with supply disruptions by considering optimal pricing strategies and sourcing levels.

The existing studies have made significant contributions in developing recovery strategies after disruptions occur in supply chain system. However, these strategies do not consider the occurrence of disruptions in special circumstances, such as the supply chain disruptions caused by the global COVID-19 outbreak, which is characterized by longer duration and wider spread than the previous epidemics or abnormal events that have occurred. Due to the large-scale impact of global supply chain during the COVID-19 pandemic, the manufacture enterprises have begun to consider utilizing the current production devices or purchasing the special devices certified by testing agencies to produce the high-demand products (masks, hand sanitizers, disinfectants and etc.) or the emergency personal protective equipment (PPE) [46,47]. In this paper, we investigate this special situation in that some or all of the original suppliers are unable to recover in the short term after a supply disruption during a pandemic, and develop a disruption recovery strategy with consideration of changing product design, in order to decrease the economic loss due to the special disruption of supply chain as possible.

3. Problem statement

In this section, the definition of the problem is presented firstly, which shows the main motivation of this research. After that, the notation and basic assumptions of the mathematical model are given.

3.1. Problem definition

In order to stop the spread of the COVID-19 pandemic, many countries adopt a lot of embargo policies that cause a large-scale reduction in the supply of raw material in the global range. As a result, many manufacture enterprises are unable to obtain sufficient raw materials and then fall into the production standstill.

In this paper, we consider a three-stage supply chain consisting of multiple suppliers of the same raw material, a manufacturing firm producing one product, and multiple retailers, as shown in Fig. 1. Suppliers in some areas affected by the outbreak may not be able to recover in the short term after a supply disruption. In addition, some suppliers may experience short-term supply disruptions or reduced supply capacity due to national embargo policies and a shrinking transportation

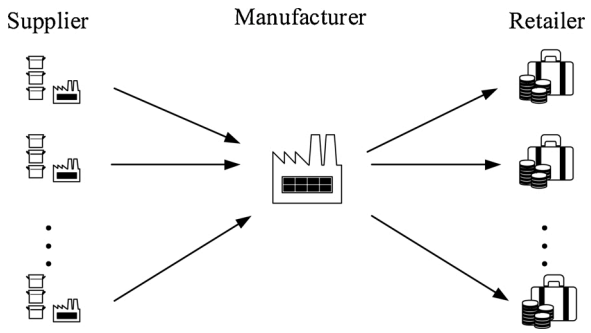

Fig. 1. Three-stage supply chain model.

industry. When a supply disruption occurs, if no action is taken, the company's capacity will drop, and out-of-stocks will occur for customer orders arriving at any given time. In this case, the customer may choose to backorder or abandon the order depending on the delivery time and will incur backorder costs or lost sales.

In order to reduce the loss of the manufacture enterprise and alleviate the disruption of supply from some or all of the original suppliers, we consider two ways at the same time in the disruption recovery strategy: one is to make an emergency purchase from the undisrupted supplier, that is, to increase the purchase quantities to keep producing the original product; the other is to change the product composition, that is, to adjust the raw materials required for the changed product, replace the original raw materials with new ones, and then select a new supplier to replace the supplier without changing the main design of product and still using the current production equipment. When the first approach is taken, the cost of emergency procurement and the quantity of raw materials that can be obtained by emergency procurement need to be considered in the model; when the second approach is taken, the cost of product change, including the procurement cost of alternative suppliers and the cost of lost sales after the product change compared with the original product, requires to be considered. Finally, an integrated decision on product change and supplier selection is conducted to establish a disruption recovery model.

Therefore, manufacturer need consider the following three important questions during the production cycle after a supply chain disruption occurs: (1) How much raw material to obtain through emergency procurement? (2) How many products to make changes and how to choose alternative suppliers? (3) How to meet the demand of different customer orders to minimize losses in case of supply-demand imbalance?

3.2. Assumptions

In order to make the study more relevant and feasible, the following basic assumptions are made.

(1) Each supplier may face two types of disruptions, that is, long-term disruptions due to the prolonged duration of the outbreak and short-term disruptions due to the embargo policy. The occurrence of disruptions at each supplier is independent each other and only related to the presence of an outbreak in that area.
(2) After the outbreak, large-scale supply disruptions occur at time 0, where the long-term disruptions are not recoverable throughout the production horizon and the short-term supply disruptions due to the embargo policy can be recovered in l cycle after the outbreak is controlled, but cause the capacity reducing.
(3) The manufacturer needs one necessary raw material to produce its product, and may choose alternative raw materials for production by changing the product design. However, there is a price difference between the changed product and the original one, which incurs a loss in cost of sales.
(4) After supply disruptions occur, taking emergency procurement requires to consider additional procurement costs, but production delay due to emergency procurement does not be taken into count, while taking product design changes requires consideration of product change costs and product change time.
(5) For all retailers, the quantity of product required for an order is determined prior to disruption and does not change during the production horizon. Retailer's order will be produced in one period and shipped immediately after production. Products in period t are delivered in period $t+1$ regardless of product transit storage.
(6) Supply shortages can result in orders not being delivered on schedule due to the forward propagation of supply disruptions. Exceeding the retailer's latest delivery date T_j requires compensation to the retailer and results in backorder costs, and exceeding the retailer's latest order cancellation time U_j can result in lost sales costs.
(7) Both transportation time and cost of raw materials and products among suppliers, manufacturers and retailers are not considered.

3.3. Notation

In order to understand the model developed in this paper, we will give the meaning of the symbols used in the model as follows.

List of indices :

i	Index for original suppliers
j	Index for retailers
k	Index for alternative suppliers
t	Index for periods
s	Index for disruption types

List of decision variables:

Y_{ti}^{s}	Quantity to be procured in t^{th} period for s^{th} disruption type from i^{th} supplier
x_{tk}^{s}	Quantity to be procured in t^{th} period for s^{th} disruption type from k^{th} alternative supplier after product change
I_t^s	The quantity of raw materials inventory in t^{th} period for s^{th} disruption type
w_{jt}^{s}	1 if j^{th} retailer's order is produced for s^{th} disruption type in t^{th} period, else 0

List of parameters

X_{ti}	Quantity to be procured in t^{th} period for normal production conditions from i^{th} supplier
v_i^s	1 if i^{th} supplier for s^{th} disruption type has not been disrupted, else 0
u_i^s	1 if i^{th} supplier for s^{th} disruption type has been disrupted due to blocking policy, else 0
O_i	Cost of ordering from i^{th} supplier
C_i	Unit procurement cost of raw materials from i^{th} supplier
E_i	Emergency unit procurement cost of raw materials from i^{th} supplier
e_k	Unit procurement cost of alternative raw materials from k^{th} alternative supplier
m_{ti}	Maximum quantity of raw material that can be supplied by i^{th} supplier in t^{th} period
n_{tk}	Maximum quantity of alternative raw material that can be supplied by k^{th} alternative supplier in t^{th} period
b_i	Loss of production capacity coefficient of i^{th} supplier
f_i	Resilience coefficient of i^{th} supplier
H	Unit holding inventory cost of raw materials
Re	Unit revenue of production
Q_t	Maximum quantity to be produced in t^{th} period
Pc	Unit cost of production
d_j	Quantity of order demand from j^{th} retailer
T_j	Last lead time for j^{th} retailer's order
U_j	Last period for j^{th} retailer to cancel the order
B_j	Unit cost of backorder for j^{th} retailer's order after delayed delivery
L_j	Unit cost of lost sales for j^{th} retailer's order after order cancellation
g	Unit cost of lost sales after product change

4. Problem model and algorithm

4.1. Mathematical representation

In this section, we propose a recovery strategy in this paper to model supplier disruption recovery targeted at minimizing the manufacturer's total cost in the event of supply disruption. We present in detail the various cost functions in recovering supply chain disruption subject to the various constraints that need to be satisfied. In addition, only the costs in the recovery window are considered due to the limited time horizon for our particular model.

The supply chain disruption in the proposed model is divided into two categories, including long-term disruptions that are not recoverable in the time horizon, and short-term disruptions that are able to recover a limited capacity after l production cycles. The set of undisrupted suppliers is I_n, the set of long-term disrupted suppliers is I_l, and the set of short-term disrupted suppliers is I_s.

The manufacturer's revenue is calculated as selling price per unit multiplied by the retailers' demand quantity and orders delivery status.

$$Rev = \sum_{t\in T}\sum_{j\in J} w_{ij}^s d_j Re \tag{1}$$

All the costs involved in the total cost of the production system TC per item are derived as follows:

(1) Fixed order cost (FOC): FOC is the cost of raw materials ordered by the manufacturer from suppliers in advance of the production schedule, independent of the number of orders and the quantity ordered, which can be expressed as the sum of the ordering costs O_i from different suppliers.

$$\mathrm{FOC} = \sum_{i\in I} O_i \tag{2}$$

(2) Raw material inventory cost (RIC): A manufacturer's raw material inventory includes a certain amount of safety stock held before a supply disruption occurs, which will be consumed after the disruption, and production to order, which may result in a backlog of raw materials. RIC can be calculated as the unit inventory cost H of raw materials multiplied by the quantity I_t^s of raw material inventory per production cycle, which can be denoted as follows:

$$\mathrm{RIC} = \sum_{t\in T} HI_t^s \tag{3}$$

(3) Production cost (PC): Considering that each product takes up a certain amount of resources when it is produced, PC is defined as the cost Pc per unit of production for each product multiplied by the total quantity $d_j w_{jt}^s$ of that product produced.

$$\mathrm{PC} = \sum_{t\in T}\sum_{j\in J} Pc * d_j w_{jt}^s \tag{4}$$

(4) Original supplier procurement cost (OPC): In case of disruptions due to the pandemic, the cost of raw materials purchased by the manufacturer from the original supplier will contain the three potential sub costs, i.e. normal procurement costs C_i from those suppliers who did not experience the disruption, emergency procurement costs E_i for additional quantities ordered after the disruption, and procurement costs C_i for suppliers who experience short-term disruptions and are able to restore supply after l production cycles. Then, OPC can be calculated by multipling the unit procurement cost of the raw materials by the purchase quantity.

$$\mathrm{OPC} = \sum_{t\in T}\sum_{i\in I} C_i Y_{ti}^s + \sum_{t\in T}\sum_{i\in I} E_i\left(Y_{ti}^s - X_{ti}v_i^s\right) + \sum_{t\in T:t\geq l}\sum_{i\in I} b_i C_i X_{ti}^s u_i^s \tag{5}$$

(5) Product change cost (PCC): Manufacturers consider design changes to some products after a supply disruption occurs, and seek new suppliers to replace original disrupted suppliers to produce new products after the product change. Product design changes require consideration of product change time p and change costs. PCC includes the cost e_k of procuring from the alternative supplier and the cost g of lost sales resulting from price differences between changed products and original products, which can be expressed as follows:

$$\mathrm{PCC} = \sum_{t\in T:t\geq p}\sum_{k\in K}(e_k + g)x_{tk}^s \tag{6}$$

(6) Backorder cost (BC): The impact of supply disruptions will propagate positively through the supply chain, ultimately causing demand-side orders not to be delivered on schedule. The backorder is an order that is not met at the time of the agreed delivery period, but can be deferred after the quantity of product produced meets the requirements. Delayed delivery requires price compensation to the customer and will incur backorder cost. BC can be calculated as the backorder cost per unit multiplied by the backordered number of units.

$$\mathrm{BC} = \sum_{j\in J} B_j d_j \left(\sum_{t\in T} w_{jt}^s - \sum_{t\in T:t\leq T_j-1} w_{jt}^s\right) \tag{7}$$

(7) Lost sales cost (LSC): When the order backorder delivery time exceeds the customer's latest waiting time, the customer will cancel the order, which will result in lost sales costs. LSC is the unit lost sales cost multiplied by the lost sales units, which can be denoted as follows:

$$\mathrm{LSC} = \sum_{j\in J} L_j d_j \left(1 - \sum_{t\in T:t\leq U_j-1} w_{jt}^s\right) \tag{8}$$

The total cost of a manufacturing company's supply chain is the sum of the seven costs listed above, including FOC, RIC, PC, OPC, PCC, BC and LSC, which can be expressed as follows:

$$\begin{aligned}\mathrm{TC} = {} & \mathrm{FOC} + \mathrm{RIC} + \mathrm{PC} + \mathrm{OPC} + \mathrm{PCC} + \mathrm{BC} + \mathrm{LSC} \\ = {} & \sum_{i\in I} O_i + \sum_{t\in T} HI_t^s + \sum_{t\in T}\sum_{j\in J} Pc * d_j w_{jt}^s + \\ & + \sum_{t\in T}\sum_{i\in I} C_i Y_{ti}^s + \sum_{t\in T}\sum_{i\in I} E_i\left(Y_{ti}^s - X_{ti}v_i^s\right) + \sum_{t\in T:t\geq l}\sum_{i\in I} b_i C_i X_{ti} u_i^s \\ & + \sum_{t\in T:t\geq p}\sum_{k\in K}(e_k + g)x_{tk}^s + \sum_{j\in J} B_j d_j \left(\sum_{t\in T} w_{jt}^s - \sum_{t\in T:t\leq T_j-1} w_{jt}^s\right) \\ & + \sum_{j\in J} L_j d_j \left(1 - \sum_{t\in T:t\leq U_j-1} w_{jt}^s\right)\end{aligned} \tag{9}$$

In summary, we propose a mixed integer linear programming (MILP) model as follow:

$$\text{Max Rev - TC} \tag{10}$$

$$\sum_{t\in T}\sum_{i\in I} X_{ti} \leq \sum_{t\in T} Q_t \tag{11}$$

$$\sum_{t\in T}\sum_{i\in I} Y_{ti}^s + \sum_{t\in T:t\geq l}\sum_{i\in I} bX_{ti}u_i^s + \sum_{t\in T:t\geq p}\sum_{k\in K} x_{tk}^s \leq \sum_{t\in T} Q_t, \forall s \in S \tag{12}$$

$$I_{t-1}^s + \sum_{i\in I} Y_{ti}^s + \sum_{i\in I} b_i X_{ti} u_i^s + \sum_{k\in K} x_{tk}^s - I_t^s = \sum_{j\in J} d_j w_{jt}^s \quad \forall t \in T, s \in S \tag{13}$$

$$X_{ti}(1 + f_i) \leq m_{ti} \quad \forall t \in T, i \in I \tag{14}$$

$$Y_{ti}^s \leq X_{ti}v_i^s(1 + f_i) \quad \forall t \in T, i \in I, s \in S \tag{15}$$

$$Y_{ti}^s \geq X_{ti}v_i^s \quad \forall t \in T, i \in I, s \in S \tag{16}$$

$$x_{tk}^s \leq n_{tk} \quad \forall t \in T, k \in K, s \in S \tag{17}$$

$$\sum_{t\in T} w_{jt}^s \leq 1 \quad \forall j \in J, s \in S \tag{18}$$

$$\sum_{j\in J} d_j w_{jt}^s \leq Q_t \quad \forall t \in T, s \in S \tag{19}$$

$$\sum_{t' \in T: t' \le t} \sum_{j \in J} d_j w_{jt}^s \le \sum_{t' \in T: t' \le t-1} \left(\sum_{i \in I} Y_{ti}^s + \sum_{k \in K} x_{tk}^s + \sum_{i \in I} bX_{ti} u_i^s \right) \quad (20)$$

$$w_{jt}^s \in \{0,1\} \quad \forall t \in T, j \in J, s \in S \quad (21)$$

$$Y_{ti}^s, I_t^s, x_{tk}^s \text{ are positive integers}, \quad \forall i \in I, j \in J, k \in K, s \in S, t \in T \quad (22)$$

Eq. (10) defines the objective function to maximize the manufacturer's total profit, along with Eqs. (1) and (9). Eqs. (11) and (12) constrain the maximum procurement quantity within the production schedule, both before and after the disruption, to not exceed the manufacturer's production capacity. Eq. (13) balances the manufacturer's procurement, product change procurement, actual production, and raw material inventories with the order requirements for each cycle after the disruption occurs. Eqs. (14)–(16) constrain the supply capacity of the original supplier before and after the disruption. Eq. (17) constrains the supply capacity of the alternative supplier chosen after the product change. Eqs. (18) and (19) constrain that each customer's order can only be produced at most once, and that the quantity of products produced for that order during the production cycle does not exceed the manufacturer's maximum capacity. Eq. (20) constrains the total quantity of products produced to not exceed the quantity of raw materials purchased from suppliers within the production schedule. Eq. (21) constrains the binary nature of the decision variable w_{jt}^s. Eq. (22) defines the decision variables Y_{ti}^s, I_t^s and x_{tk}^s as positive integers.

4.2. Solution approach

In the existing literature, various optimization tools have been widely used to solve small and medium-sized problems. Considering that the model developed in this paper is a mixed-integer linear programming (MILP) model, we propose a heuristic algorithm for solving the model. we will use IBM ILOG CPLEX 12.10.0 and matlab2018b Optimization Toolbox as the solution approach. With its integrated development environment, descriptive modeling language, and built-in tools, ILOG CPLEX can solve mixed-integer linear programming problems quickly and reliably.

In the solving process, we firstly solve for the raw material procurement and production under normal production conditions with the goal of maximizing the manufacturer's total profit; and then we classify the types of disruptions faced by suppliers; and later on, we solve to minimize the manufacturer's total cost without any recovery strategy after a supply disruption occurs; and finally we solve the model developed by the combined recovery strategy proposed in this paper.

The main steps of the proposed solution algorithm are presented as follows:

Step 1: Input all parameters on the production system and get X_{ti};

Step 2: Classify the disruption types of suppliers and assign values to u_i^s, v_i^s according to the classification results;

Step 3: Set $s = 1$ for the first disruption type and input disruption scenario;

Step 4: Put $s = 1, 2, 3\ldots$ for disruption for all suppliers;

Step 5: Solve the mathematical model under the updated disruption scenario;

Step 6: Update the values of Y_{ti}^s and x_{tk}^s as the revised procurement lot size from Step 5 and record the revised production plan;

Step 7: Output the final results.

5. Numerical experiments

In this section, detailed numerical examples are conducted to verify the feasibility of the proposed model. Firstly, we use a randomly generated data-set with values assigned to each parameter of suppliers, manufacturers and retailers. Next, the proposed MILP model simultaneously optimize product and procurement plan considering all resource constraints related to suppliers, manufacturers and retailers, where the objective is maximizing total profit for the manufacturer under different recovery strategies. Finally, some numerical experiments are conducted and the experiment results of lost manufacturer revenue due to disruptions are compared. In addition, we perform a sensitivity analysis on the different parameters to characterize the effect of their changes on the results. It is assumed that 6 suppliers provide raw materials before the disruption occurs that the products produced by the manufacturer will be supplied to each of the 8 customers, and that the production horizon for the recovery period after the disruption consists of 10 time periods. There are 3 alternative suppliers to choose from after a product design change, and the product design change time p is $2T$.

The supply side may face long-term disruptions due to large-scale spread of the epidemic or short-term disruptions due to the embargo policy. It is assumed a random value between $2T$ and $4T$ for the recovery time l after a short-term disruption. To demonstrate the proposed model, two supply disruption types that a manufacturer may face are discussed, including long-term disruption that cannot be recovered within a production recovery plan, and both long-term disruption and short-term disruption that are considered simultaneously. Therefore, it is assumed that suppliers 1,3,4, and 5 have long-term disruptions in illustration 1, where $I_n = \{2,6\}$, $I_l = \{1,3,4,5\}$, $s = 1$, and suppliers 1 and 2 experience long-term disruptions and suppliers 4 and 6 face short-term disruptions in illustration 2, where $I_n = \{3,5\}$, $I_l = \{1,2\}$, $I_s = \{4,6\}$, $s = 1$.

5.1. Computational results

The supplier parameter information is shown in Table 1, which describes the values of maximum supply quantity m_{ti}, loss of production capacity coefficient b_i, resilience coefficient of supply capacity f_i, fixed order cost O_i, unit procurement cost C_i, and emergency procurement cost E_i.

Parameters related to product changes are shown in Table 2, which describes the values of maximum supply quantity n_{tk}, unit procurement cost e_i, and the cost of lost sales g. In addition, product change time $p = 2T$.

The retailer's parameter information is shown in Table 3, which describes the order quantity d_j, the latest delivery cycle T_j for the retailer's order, the latest cycle U_j for the retailer's order cancellation, the unit backorder cost B_j, and the cost of lost sales L_j, where $3T$ represents the third time period of the production schedule.

We give the values of the other parameters in the model, including the manufacturer's production capacity $Q_t = 3000$, the manufacturing unit cost $Pc = 6$, the raw material inventory cost $H = 2$, and the product revenue per unit $Re = 30$.

Under normal production conditions, the raw material procurement from the original supplier is calculated to maximize the manufacturer's total profit, and the results are shown in Table 4.

In the case of different types of disruptions to suppliers, when the manufacturer does not adopt any recovery strategy, the raw material procurement from the original suppliers is calculated to maximize the manufacturer's total profit, and the results of illustration 1 and illustration 2 are shown in Table 5. In case of supply disruptions, an emergency procurement strategy will be implemented immediately, and the

Table 1
Supplier parameters.

Supplier	m_{ti}	b_i	f_i	O_i	C_i	E_i
S1	500	0.75	0.25	2000	12	5
S2	400	0.8	0.25	1800	11	4
S3	400	0.8	0.2	1800	10	4
S4	500	0.75	0.2	2000	11	3
S5	600	0.8	0.3	2100	12	4
S6	500	0.7	0.25	2000	11	5

Table 2
Product design change parameters.

Supplier	n_{tk}	e_i	g
A1	400	10	5
A2	450	9	5
A3	500	11	5

Table 3
Retailer parameters.

Retailer	d_j	B_j	L_j	T_j	U_j
R1	2100	4	8	3 T	4 T
R2	2300	3	6	3 T	5T
R3	2400	5	10	5T	6T
R4	2500	5	10	5T	7T
R5	2500	4	8	6T	7T
R6	2400	4	8	8T	9T
R7	2100	3	6	8T	10T
R8	2300	3	6	9T	10T

Table 4
Manufacturer's procurement of raw materials and maximum total profit.

X_{t1}	X_{t2}	X_{t3}	X_{t4}	X_{t5}	X_{t6}	Total Profit
400	320	333	416	198	400	220,812

Table 5
Manufacturer's maximum profit without any measures.

s	X_{t1}	X_{t2}	X_{t3}	X_{t4}	X_{t5}	X_{t6}	Total Profit
1	0	320	0	0	0	400	−227118
2	0	0	333	$0(t \le 3T)$ $312(t > 3T)$	198	$0(t \le 3T)$ $280(t > 3T)$	−161452

corresponding results are shown in Table 6.

It can be seen that when suppliers have supply disruptions, the manufacturer's total profit will decrease as the number of disrupted suppliers increases, and the manufacturer will suffer a significant loss if it does not take timely recovery measures. As can be seen from Table 5, without any recovery strategy, the supply disruptions in illustration 1 and 2 will result in losses to the manufacturer of 447,930 and 382,264 respectively. As can be seen from Table 5, when only an emergency sourcing strategy is adopted, it will result in losses to the manufacturer of 248,132 and 191,880 respectively.

When adopting the product design change and emergency procurement combination recovery strategy proposed in this paper, raw material procurement from original suppliers with emergency procuring strategy and the manufacturer's maximum profit are shown in Table 7, and the manufacturer's procurement at alternative suppliers after product change time $2T$ for each time period are shown in Table 8.

In the same supply disruption scenario, the manufacturer's combined recovery strategy results in losses of 99,882 and 43,450 respectively. Therefore, comparing the results obtained by manufacturers with different strategies after a supply disruption, it can be seen that a combination of emergency procuring and product design change to add alternative suppliers can effectively reduce the manufacturer's losses.

Table 6
Manufacturer's maximum profit after emergency procurement.

s	Y_{t1}	Y_{t2}	Y_{t3}	Y_{t4}	Y_{t5}	Y_{t6}	Total Profit
1	0	400	0	0	0	450	−27320
2	0	0	399	$0(t \le 3T)$ $312(t > 3T)$	226	$0(t \le 3T)$ $280(t > 3T)$	28,932

Table 7
Manufacturer's maximum profit after combination recovery strategy.

s	Y_{t1}	Y_{t2}	Y_{t3}	Y_{t4}	Y_{t5}	Y_{t6}	Total Profit
1	0	400	0	0	0	500	120,930
2	0	0	399	$0(t \le 3T)312$ $(t > 3T)$	257	$0(t \le 3T)280$ $(t > 3T)$	177,362

Table 8
Manufacturer's procurement of alternative suppliers after product change.

s	k	x_{3k}	x_{4k}	x_{5k}	x_{6k}	x_{7k}	x_{8k}	x_{9k}
	1	400	400	400	400	400	400	0
1	2	450	450	450	450	450	450	100
	3	500	500	500	500	500	500	0
	1	400	302	302	400	400	400	400
2	2	450	450	450	450	450	450	450
	3	500	500	500	390	500	500	500

5.2. Sensitivity analysis

Manufacturer's total cost after disruptions vary with different parameters. In this section, we will analyze the change in manufacturer's total cost by performing a sensitivity analysis on E_i, B_j, L_j and g for the cases of illustration 2. For characterizing the impact, the sensitivity analysis is performed different parameters, and only one parameter is changed for each analysis, and the remainder is kept the same as in Section 5.1. We will change the parameters to -50 %, -25 %, +25 %, and +50 % of the original values to solve for the results, and details are given in Table 9.

As can be seen in Table 9, the manufacturer's total profit after adopting the recovery strategy is more sensitive to the loss of sales resulting from the product change and can quickly change the resultant values with small changes in the parameter values.

Figs. 2 and 3 show the changes of a manufacturer's total profit with product change sales loss and product change design time respectively after the disruption. It can be seen that total profit decreases as product change cost and time increase, and in particular, product change design time can have a large impact on total profit. Figs. 4 and 5show the changes of a manufacturer's total profit with backorder cost and lost sales cost respectively. The backorder cost can have a large impact on total profit because of compromises in the production quantities. However, the manufacturer's profit will increase significantly when the compensation price for backorders is low. The increment in lost sales cost causes a linear decrease in overall profit for the production system.

Table 9
Sensitivity analysis regarding key parameters for illustration 2.

Parameters	Parameter change (%)	Total profit	Change in profit (%)
g	−50%	203,177	+14.55 %
	−25%	190,269	+7.28 %
	+25%	164,454	−7.28%
	+50%	151,547	−14.55%
E_i	−50%	177,612	+0.14 %
	−25%	177,487	+0.07 %
	+25%	177,237	−0.07%
	+50%	177,112	−0.44%
B_j	−50%	184,462	+4.01 %
	−25%	179,087	+0.97 %
	+25%	175,637	−0.97%
	+50%	173,912	−1.95%
L_j	−50%	184,262	+3.89 %
	−25%	180,812	+1.95 %
	+25%	173,912	−1.95%
	+50%	170,462	−3.89%

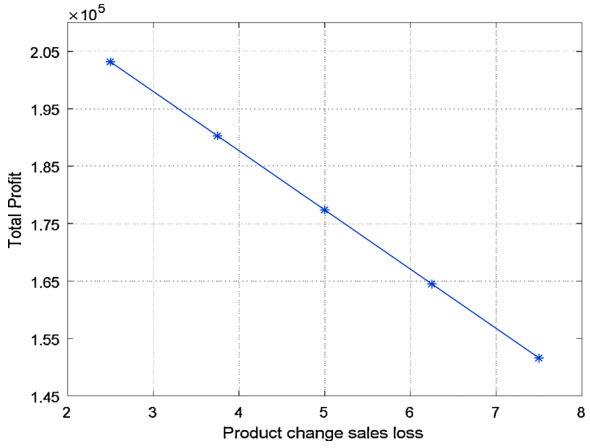

Fig. 2. Changes of total profit with product change sales loss.

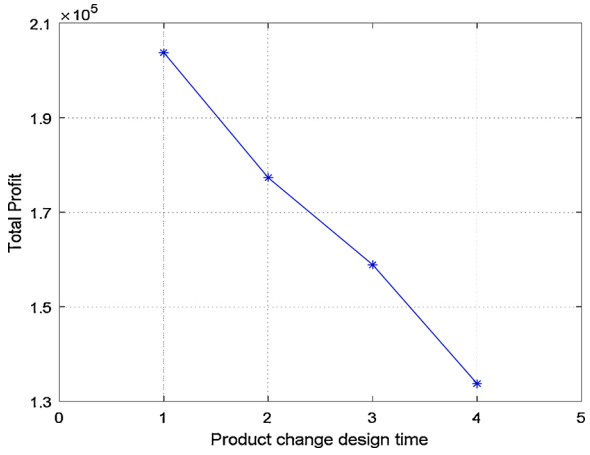

Fig. 3. Changes of total profit with product change design time.

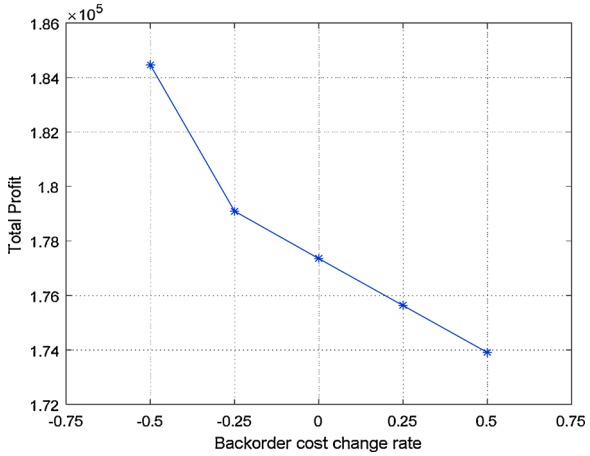

Fig. 4. Changes of total profit with backorder cost change rate.

6. Managerial insights

In this paper, we consider a three-tier supply chain system in that demand is deterministic but sensitive to both price and delivery time. When its supply chain is disrupted by the COVID-19 pandemic, the manufacturer's optimal disruption recovery strategy is analyzed by combining emergency procurement on the supply side and product changes by the manufacturer as well as backorder price compensation

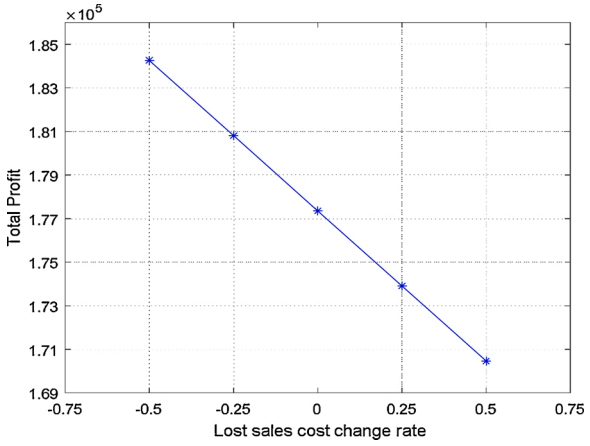

Fig. 5. Changes of total profit with lost sales cost change rate.

on the demand side. The approach of using numerical problems to develop a recovery plan after a production disruption occurs can provide managers with examples to solve disruption problems in real-world environments. Our results provide decision makers with the following insights.

(1) This paper presents a model for combined disruption recovery strategies under uncertainty during the COVID-19 pandemic. The proposed model can help managers consider factors such as market demand, machine capacity, and supply situation in the decision-making process of designing a resilient supply chain to cope with unexpected disruptions similar to those caused by a pandemic outbreak.
(2) Cost and time factors play different roles in designing an optimal disruption recovery strategy. The cost factor takes into account the additional procurement costs arising from emergency purchases, the change costs arising from product changes and their resulting lost sales, and the compensation costs to customers for backorder. How to determine raw material purchases, order production allocations and compensation levels for the recovery period essentially depends on time factors such as customer sensitivity to wait times and the duration of disruptions.
(3) When the supply interruption may exist for a long time, the manufacturer can take into account factors such as out-of-stock situation, product design change time, alternative supplier procurement cost and supply capacity, etc., to make certain degree of design changes to the products produced, in order to achieve the purpose of rapid resumption of production, reduce the disruption loss and reduce the impact on corporate reputation.
(4) For short-term disruptions, the optimal disruption recovery strategy mainly consists of emergency procurement. For long-term disruptions, a combined strategy consisting of both emergency procurement and product change is optimal for certain time periods of the production horizon.
(5) The sensitivity analysis reveals that the time of product design changes and the sales loss incurred after product changes are more likely to pose an impact upon the manufacturer's total cost. Therefore, managers should consider how to reduce time cost and sales loss in actual system.

7. Conclusions

In this paper, we develop a disruption recovery strategy for manufacturing companies in order to cope with the large-scale disruptions caused by the COVID-19 pandemic. When some or all of suppliers cannot recover quickly in a short period, the manufacturer would consider to change the product type partly and select the new suppliers

that provide the raw material for the changed product in order to decrease the profit loss caused by this special disruption of supply chain. A MILP model is presented with combining emergency procurement on the supply side and product changes by the manufacturer as well as backorder price compensation on the demand side. Numerical experiments show that although changing product could incur additional procurement cost and sales profit loss, it can effectively decrease the impact of large-scale supply chain disruptions. In addition, several managerial insights are also provided for decision-makers to address the real-world disruption problems of supply chain.

Despite all these efforts, this study still has a few limitations. For instance, the influence of demand fluctuation and the transshipment cost have not been taken into count, which may often occur during the outbreak in fact. In addition, other factors exist in practice, such as multiple types of products, procurement costs of different raw materials, and so on. Thus, future studies may incorporate these factors into the present disruption recovery model.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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References

[1] Hendricks KB, Singhal VR. Association between supply chain glitches and operating performance. Manag Scie 2005;51(5):695–711.
[2] Ivanov D, Pavlov A, Sokolov B. Optimal distribution (re)planning in a centralized multistage supply network under conditions of the ripple effect and structure dynamics. Eur J Oper Res 2014;237(2):758–70.
[3] Pavlov A, Ivanov D, Werner F, Dolgui A, Sokolov B. Integrated detection of disruption scenarios, the ripple effect dispersal and recovery paths in supply chains. Ann Oper Res 2019;15:1–23.
[4] Kim SH, Tomlin B. Guilt by association: strategic failure prevention and recovery capacity investments. Manag Scie 2013;59(7):1631–49.
[5] Ocampo L, Masbad JG, Noel VM, Omega RS. Supply-side inoperability input–output model (SIIM) for risk analysis in manufacturing systems. Int J Ind Manuf Syst Eng 2016;41:76–85.
[6] Ji W, Wang L. Big data analytics based fault prediction for shop floor scheduling. Int J Ind Manuf Syst Eng 2017;43:187–94.
[7] Asian S, Nie X. Coordination in supply chains with uncertain demand and disruption risks: existence, analysis, and insights. IEEE Trans Syst Man Cybern Syst 2014;44:1139–54.
[8] Hosseini S, Al Khaled A, Sarder MD. A general framework for assessing system resilience using Bayesian networks: a case study of sulfuric acid manufacturer. Int J Ind Manuf Syst Eng 2016;41:211–27.
[9] Rajesh R. Flexible business strategies to enhance resilience in manufacturing supply chains: an empirical study. Int J Ind Manuf Syst Eng 2020. https://doi.org/10.1016/j.jmsy. 2020.10.010.
[10] Craighead CW, Blackhurst J, Rungtusanatham MJ, Handfield RB. The severity of supply chain disruptions: design characteristics and mitigation capabilities. Decision Scie 2007;38:131–56.
[11] Chowdhury MMH, Quaddus M. Supply chain resilience: conceptualization and scale development using dynamic capability theory. Int J Prod Econ 2017;188:185–204.
[12] Dubey R, Gunasekaran A, Childe SJ, Papadopoulos A, Blome C, Luo Z. Antecedents of resilient supply chains: an empirical study. IEEE Trans Eng Manag 2019;66(1):8–19.
[13] Queiroz MM, Ivanov D, Dolgui A, Wamba SF. Impacts of epidemic outbreaks on supply chains: mapping a research agenda amid the COVID-19 pandemic through a structured literature review. Ann Oper Res 2020. https://doi.org/10.1007/s10479-020-03685-03687.
[14] Ivanov D. Predicting the impacts of epidemic outbreaks on global supply chains: a simulation-based analysis on the coronavirus outbreak (covid-19/sars-cov-2) case. Transport Res Part E: Logist Transport Rev 2020;136:101922.
[15] Ivanov D, Dolgui A. OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: managerial insights and research implications. Int J Prod Econ 2021;232:107921.
[16] Laing T. The economic impact of the Coronavirus 2019(Covid-2019): implications for the mining industry. Extrac Ind and Socie 2020;7:580–2.
[17] Li Y, Zobel CW. Exploring supply chain network resilience in the presence of the ripple effect. Int J Prod Econ 2020;228:107693.
[18] Ivanov D, Dolgui A, Sokolov B, Ivanova M. Literature review on disruption recovery in the supply chain. Int J Prod Res 2017;55(20):6158–74.
[19] Golmohammadi A, Hassini E. Review of supplier diversification and pricing strategies under random supply and demand. Int J Prod Res 2020;58(11):3455–87.
[20] He Y, Li S, Xu H, Shi C. An in-depth analysis of contingent sourcing strategy for handling supply disruptions. IEEE Trans Eng Manag 2020;67:201–19.
[21] Islam MT, Azeem A, Jabir M, Paul A, Paul SK. An inventory model for a three-stage supply chain with random capacities considering disruptions and supplier reliability. Ann Oper Res 2020. https://doi.org/10.1007/s10479-020-03639-z.
[22] Ivanov D, Dolgui A, Sokolov B. Scheduling of recovery actions in the supply chain with resilience analysis considerations. Int J Prod Res 2018;56(19):6473–90.
[23] Ivanov D. Viable supply chain model: integrating agility, resilience and sustainability perspectives—lessons from and thinking beyond the COVID-19 pandemic. Ann Oper Res 2020. https://doi.org/10.1007/s10479-020-03640-6.
[24] Xu H. Minimizing the ripple effect caused by operational risks in a make-to-order supply chain. Int J Phys Distrib Logist Manag 2020;50(4):381–402.
[25] Eckert C, John AP, Ae C, Zanker W. Change and customisation in complex engineering domains. Res Eng Design 2004;15(1):1–21.
[26] Li Y, Zhao W, Zhang J. Resource constrained scheduling of design changes based on simulation of change propagation process in the complex engineering design. Res Eng Design 2019;30(1):21–40.
[27] Dolgui A, Ivanov D, Sokolov B. Ripple effect in the supply chain: an analysis and recent literature. Int J Prod Res 2018;56(1-2):414–30.
[28] Ivanov D, Sokolov B, Dolgui A. The ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience' in disruption management. Int J Prod Res 2014;52(7):2154–72.
[29] Lee HL, Padmanabhan V, Whang S. Information distortion in a supply chain: the bullwhip effect. Manag Scie 1997;43(4):546–58.
[30] Ivanov D, Sokolov B. Simultaneous structural-operational control of supply chain dynamics and resilience. Ann Oper Res 2019;283(1-2):1191–210.
[31] Li Y, Chen K, Collignon S, Ivanov D. Ripple effect in the supply chain network: forward and backward disruption propagation, network health and firm vulnerability. Eur J Oper Res 2021;291(3):1117–31.
[32] Zhang J, Chen X, Fang C. Transmission of a supplier's disruption risk along the supply chain: a further investigation of the Chinese automotive industry. Prod Plan Control 2018;29(9):773–89.
[33] Knemeyer AM, Zinn W, Eroglu C. Proactive planning for catastrophic events in supply chains. J Oper Manag 2009;27:141–53.
[34] Pal B, Sana SS, Chaudhuri KS. A multi-echelon production–inventory system with supply disruption. Int J Ind Manuf Syst Eng 2014;33(2):262–76.
[35] Pal B, Sana SS, Chaudhuri KS. A mathematical model on EPQ for stochastic demand in an imperfect production system. Int J Ind Manuf Syst Eng 2013;32(1):260–70.
[36] Torabi SA, Baghersad M, Mansouri SA. Resilient supplier selection and order allocation under operational and disruption risks. Transp Res Part E Logist Transp Rev 2015;79:22–48.
[37] Paul SK, Sarker R, Essam D, Lee PTW. A mathematical modelling approach for managing sudden disturbances in a three-tier manufacturing supply chain. Ann Oper Res 2019;280(1-2):299–335.
[38] Tomlin B. On the value of mitigation and contingency strategies for managing supply chain disruption risks. Manag Scie 2006;52(5):639–57.
[39] Xia Y, Yang MH, Golany B, Gilbert S, Yu G. Real-time disruption management in a two-stage production and inventory system. IIE Trans 2004;36(2):111–25.
[40] Hishamuddin H, Sarker RA, Essam D. A disruption recovery model for a single stage production-inventory system. Eur J Oper Res 2012;222(3):464–73.
[41] Paul SK, Sarker R, Essam D. Managing risk and disruption in production-inventory and supply chain systems: a review. J Ind Managt Opt 2016;12(3):1009–29.
[42] Kaur H, Singh SP, Garza-Reyes JA, Mishra N. Sustainable stochastic production and procurement problem for resilient supply chain. Comput Ind Eng 2020;139:105560. 1-105560.14.
[43] Malik AI, Sarkar B. Disruption management in a constrained multi-product imperfect production system. J Manuf Syst 2020;56:227–40.
[44] Ivanov D, Rozhkov M, Ru M-O. Coordination of production and ordering policies under capacity disruption and product write-off risk: an analytical study with real-data based simulations of a fast-moving consumer goods company. Ann Oper Res 2020;291:387–407.
[45] Gupta V, Ivanov D, Choi TM. Competitive pricing of substitute products under supply disruption. Omega 2021;101:102279.
[46] Paul S, Chowdhury P. A production recovery plan in manufacturing supply chains for a high-demand item during COVID-19. Int J Phys Distrib Logist Manag 2021;51(2):104–25.
[47] Vanhooydonck A, Van Goethem S, Van Loon J, Vandormael R, Vleugels J, Peeters T, et al. Case study into the successful emergency production and certification of a filtering facepiece respirator for Belgian hospitals during the COVID-19 pandemic. J Manuf Syst 2021. https://doi.org/10.1016/j.jmsy.2021.03.016.