




## Article

# COVID-19 Challenges: Can Industry 4.0 Technologies Help with Business Continuity?

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**Abstract:** The COVID-19 pandemic has halted economic activities and made business dynamics much more challenging by introducing several additional operational, structural, and managerial constraints. The problem has affected global supply chains in many ways, and has questioned their long-term continuity. On the other hand, Industry 4.0 is an emerging phenomenon. However, there is a need to investigate how Industry 4.0 technologies may play a potential role in sustaining business operations to ease unprecedented causalities. The current research aims to investigate the potentiality of Industry 4.0 technologies to solve the COVID-19 challenges for long term sustainability. From an exploratory literature analysis coupled with the Delphi method, keeping in view the situation of the pandemic, ten challenge groups that have affected global business dynamics were identified. A questionnaire was developed with the aim of accumulating industrial and academic experts to evaluate the degree of influence and interrelationship among the identified challenges. The Decision Making, Trial and Evaluation Laboratory (DEMATEL) approach was deployed to further analyze the challenges for the categorization of these into causes and effects, further prioritizing them for better decision making. The prioritized challenges from the list of causes were governmental policies and support, followed by real access to customers and a lack of infrastructure. Additionally, these challenges were further evaluated through the expert opinion of Industry 4.0 systems experts and strategic-level supply chain experts to potentially gauge the potency of Industry 4.0 technologies to solve COVID-19-induced challenges. The outcomes of this research (which used Delphi integrated with a DEMATEL approach) are expected to support businesses in formulating strategies with the aim of business continuity in combating future disruptions caused by COVID-19-like pandemics.

**Keywords:** Industry 4.0; smart manufacturing; COVID-19; business dynamics; business continuity; challenges; DEMATEL



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## 1. Introduction

Recently, at the dawn of 2020, the world started to face a significantly huge, unmatched, and unprecedented pandemic, COVID-19. When businesses ranging from the micro to large scale were looking forward to gradual responsiveness and the adoption of novel state-of-the-art technologies to step into the dawn of the most recent industrial revolution, the health crisis caught the world unprepared and affected large communities, business dynamics and economical activities [1]. The dependence of operations on humans revoked the continuity of operations due to human–human transmission of the virus. Similarly, the businesses and people were dealing with new challenges, such as the fear of contagion, remonstrance of quarantine, and unparalleled losses of human lives, as well as the economic perspective. The extraordinary COVID-19 pandemic of recent times has affected several businesses and, in fact, whole supply chains, and has infected more than 76.6 million people,

with around 1.7 million deaths from 200 territories, countries, and states as of 12 December 2020 [2]. There have been 18 million cases in the United States, 10 million in India, seven million in Brazil, and two million in Russia, France, Turkey, the United Kingdom and Italy each. Moreover, there have been hundreds and thousands of critical cases and deaths, making it a global pandemic. The situation of emergency because of the pandemic was launched globally on 11 March 2020 [3]. The impacts have gained the attention of many scholars, researchers, and industrial tycoons to analyze the situation. Moreover, there are exponentially increasing negative concerns regarding economic activities, businesses, global policies, and government subsidies. An insight of the key challenges is important for the formulation of policies and solution pathways for business continuity. This highlights the urgent need to answer the following question:

**RQ1:** What are the potential challenges faced by supply chains, specifically manufacturing sectors, in carrying out sustainable operations during the COVID-19 pandemic?

The major challenge faced in the initial days of COVID-19 was the lockdown, which had a reported impact on 94% of enterprises among Fortune 1000 companies [4]. A global survey of 10,000 small businesses reported that 96% were severely affected by the consequences of the crisis, such as hindrance in the continuity of business and logistical operations [5]. Similarly, 51% reported severe damage to revenues and bankruptcy after three months of the pandemic, and consequently lockdown. Worsening the conditions, 67% could not access emergency funding [5]. Likewise, the prime concerns caused by the pandemic include the transportation of workers safely to the production facility, the product sales drop and the consequent expenses of protection equipment, and disturbed logistical and operations activities [6]. The manufacturing sector contributes to global GDP by ~16%. The COVID-19 crisis resulted in the sharpest downfall of global GDP (−4.36%) since 1990 [7]. The GDP of the Euro-zone dropped by 3.8% in the very first quarter, exhibiting its sharpest decrease since 1995. Similarly, a significant fall from −4.7 to −5.8% was experienced in countries like Italy, Spain, and France. Similarly, the economies of the US and UK declined in a similar quarter by 1.2% and 2%, respectively [8]. The scale of disruptions could be imagined by the report, which mentioned that the world's richest tycoons suffered the loss of \$444 B in just one-week, 21–28 February 2020 [9]. These circumstances lead towards us finding the key challenges and prioritizing them to devise better solution frameworks.

**RQ2:** How can these challenges be prioritized and categorized from a strategy perspective under the paradigm of sustainability?

Before COVID-19, the manufacturing sector of various countries was not majorly dependent on globalization. If there are few supplier or demand nodes unavailable, the continuity of business operations is not affected [10] because, through parallel nodes, the load is transferred to another network loop. However, with the increase in supply chain partnering, the global focus on transnational and multidomestic strategies increased the dependance on global partners [11]. Recently, revolutionary technologies have been developed to support the manufacturing sector and overall supply chains in the agility, resilience and sustainability perspectives. Information and communication technologies—including cyber-physical systems, transparency, systems optimization, the internet of things, cloud computing and blockchain—are helping businesses in the 21st century to be more competitive and differentiative with new competencies [12]. On Chinese New Year's eve, many workers went on vacations, disrupting the production plans of factories. Therefore, to avoid such ripple effects, which happen with low frequency but high altitude, cloud edge-based computing setup helps us to improve manufacturing systems by decreasing the dependency of the system on labor [13]. Moreover, in order to assist managerial and superior activities, the use of virtual reality and synchronized remote activity control technology emerged as survival strategy. Likewise, these technologies helped governments at different levels, businessmen, practitioners, and decision makers to jointly strategize a way out of the crisis. It also helped us to organize operations by engaging employees [1,14].

This article contributes to the business analysis body of knowledge. Firstly, with the sprawl of negative impacts of COVID-19 on operations and businesses, the research paves the way for policy makers by reviewing modern technologies in the fourth industrial revolution and their potential benefits during a health crisis. Moreover, it examines the looming challenges faced by global supply chains, especially the manufacturing sector, for their commitment to sustainable policies in the wake of this global pandemic. In addition to this, a contribution is made to existing business operations sustainability literature by mathematically shedding light on the causes and effects using illustrative cases and empirical evidence. Furthermore, the potential Industry 4.0 technologies are examined, and are undertaken to resolve the global pandemic and its aftermath. The research rectifies the gap by evaluating the challenges in the strategic perspective and suggesting promising technologies to combat the challenges, and to deliver a sustainable agenda in this new normal.

The rest of the article is organized as follows. Section 1.1 provides the background of the supply chains and epidemic outbreaks. Section 1.2 highlights the research problem and objectives to be addressed through the analyses. Section 2 introduces the literature on Industry 4.0 technologies and highlights the potential benefits in terms of novel circumstances and the challenges faced during COVID-19 pandemic. Section 3 describes the methodology of the overall research project. Section 4 gives the results of the analyses of the challenges, followed by Section 5, which serves as the conclusion, underscores the related implications, and provides the limitations of the study with the possible future research directions.

### 1.1. SCs and Epidemic Outbreaks

Businesses use integrated supply chain models to avoid disruptions causing bullwhip effects. The approaches of an accurate pull system, vendor-managed inventories, and standardization with the reduction of lot size maximized the confidence and throughput of the manufacturing system [12,14]. In addition to this, firms use multiple suppliers locally as well as globally to minimize risks from natural hazards or man-made circumstances. Disasters that disrupt supply chains include tsunamis, earthquakes, terror activities and other potential epidemic outbreaks [15]. Business tycoons use multiple suppliers to effectively mitigate the risks of supply disturbances. The probability of  $n$  suppliers being disturbed is calculated through Equation (1) [11].

$$P(n) = D_S + (1 - D_S) \times U^n \quad (1)$$

The probability of a disaster at very large scale affecting possibly all of the suppliers is  $D_S$ . If the probability increases, the benefit of retaining multiple suppliers vanishes, as all will not be available. However,  $U$  is the probability of a unique event disturbing a single supplier. With the increase in the likelihood of the unique event, the requirement for additional suppliers increases. In order to decrease the failure probability of a system, geographically distributed suppliers are used. These disasters lead to ripple effects because of supply chain uncertainties [9]. Moreover, this leads to the creation of a bullwhip effect which fluctuates prices, and other shortage gaming is initiated [16]. The measure of the bullwhip effect in a supply chain can be calculated in a simple manner, as shown in Equation (2) [11].

$$\text{Bullwhip} = \frac{\text{Variance of orders}}{\text{Variance of demand}} = \frac{\sigma_{orders}^2}{\sigma_{demand}^2} \quad (2)$$

Epidemic outbreaks are special form disasters which involve SC risks of long-term existence and propagation producing ripple effects in highly uncertain environments [17]. In the 1900s, an outbreak of Influenza all over the world killed around 50 M people. This put pressure on continuing business activities because of human resource absence. Similarly, Ebola did damage to economies, human lives, and businesses [15]. Furthermore, Cholera, Malaria and COVID-19 affected the manufacturing sector and supply chains

for billions of dollars [17]. For example, the COVID-19 crisis has resulted in the sharpest downfall of global GDP (−4.36%) experienced since 1990 [7]. The pandemics and outbreaks affected humanity and businesses significantly [17]. This has led to the improvement of the existing disease management, disaster management, and system reliability capabilities [9]. The prime challenges include coping with the unavailability of resources such as human resources. In recent times, the dependency on human resources decreased remarkably by introducing robotic and automated systems [18]. Ebola and Influenza were prominent outbreaks in the past which killed millions of people and wiped out many businesses [17]. Since the start of the pandemic, a serious lockdown in many areas was announced, which directly affected production activities [17,19]. Moreover, the disaster has affected economies by billions of dollars [20]. The above conditions leave the practitioners to question which is the most important challenge requiring urgent focus to strengthen business sustainability initiatives.

**RQ3:** Which major challenge should be resolved on a priority basis by supply chains, specifically manufacturing sectors, for sustainable business models under disrupted conditions?

## 1.2. Industry 4.0

### 1.2.1. Industry 4.0 Technologies

The fourth revolution in manufacturing systems brought various technologies, which help in several aspects. Robotics, with the modified concept of a human–robot workplace, played a very important role in the pandemic [18]. Nardo [21] developed a conceptual framework of Industry 4.0 for industrial management. From disease prevention to helping to carry out business operations, the technology improved the reliability of systems. Therefore, the challenges faced in the COVID-19 era put pressure on businesses for the transition of the operations towards Industry 4.0 technology-integrated solutions. The prime focus is on how Industry 4.0 can help solve the challenges caused by the unprecedented circumstances. This problem requires rigorous brainstorming on which technology, if implemented, can solve which challenge promptly.

**RQ4:** Which major challenges can be resolved by Industry 4.0 technologies?

The prominent technologies in regard to digital planning are big data analytics and cloud computing. Consequently, big data technology helps in finding trends and useful information [22]. It aids in trackability and traceability, giving more control of the production and product to the customer, along with optimized resource utilization. Cloud computing helps in effective decision making. In addition, technologies like systems integration and internet-of-things-equipped industries help in upgrading system-level reliability [23], and also for digital sourcing and logistics. Digital support systems help in maintaining operational excellence through autonomous robotics and augmented reality (AR). The system integration technology which ensures communication between machines and nodes in supply chains helped in optimizing related factors to optimize results accordingly. The Industry 4.0 technologies which potentially represent all of Industry 4.0's potential to help in tough times are provided in Table 1. Similarly, a brief description introducing the relevant technology is provided. The possibility of the technologies to counter the COVID-19-induced challenges needs to be assessed by technology experts for better policy making.

**RQ5:** What is the potentiality of Industry 4.0 technologies to resolve these challenges for long term sustainability?

Intelligent industrial systems, often known as cyber physical systems, as per the National Institute of Standards and Technology, ensure the integration of physical components/hardware with the software for effective interaction between machines, plants, and overall supply chains. The systems in smart factories use highly specialized software and interface for the integration of systems' functionality with the digital environment for vertical or horizontal integration [24].

**Horizontal integration:** The information technology networks and production systems are integrated for effective data and information communication between machines, people, and firms, which could be in house or at remote places situated in different geographic locations in the overall supply chain. The horizontal integration links the IT technologies with manufacturing systems through an automatic control system for better production and planning goals.

**Vertical integration:** The internet of things and the digital components provide access to manufacturing systems through an integrated framework. The control in vertical integration is made possible in geographically different areas by integrated data and information. The integrated control of the production floor helps the higher management to manage the production at the firm level [25]. The vertical integration is the integration of IT technologies and production systems in different hierarchies. The physical sensors help in recording the data, and big data analytics, the internet of things and artificial intelligence support the production management. The multi-model interface with data, machine, management processes and the internet help in forming digital networks for effective decision making. The vertical and horizontal integration cooperates with the machines, internet, people, and value chain in real time scenarios.

The cyber physical systems basically represent mechanical systems coupled with information technology systems and/or digital components. These communicate with each other autonomously. Industry 4.0 technologies provide the following capabilities [26]:

- **Functional Compatibilities:** The intelligent machines are capable of exchanging information between mechanical components and people through the internet and internet of things, forming an intelligent factory, also known as a smart factory.
- **Decentralized Controlling Capability:** The separate components in the smart factory are capable of making independent decisions in the direction of circumstances without requiring local or individual control [25].
- **Virtual Capability:** The digital twin of the industry is the virtual replica of the smart factory produced by the big data generated from sensors installed in the production processes. This helps monitor the production and other related metrics for management.
- **Data:** Data is the most valuable asset for an industry. Industry 4.0 provides the opportunity to gather and analyze data for effective decision-making in real-time scenarios [27].
- **Smart Services Orientation:** The digitally integrated systems help customers track the data while using the products, and integrates the maintenance and other important checks for smart users.
- **Flexible Systems:** The smart factories are capable of mass customization in ever-changing requirements by using mass production and planning for customized solutions [24].
- **Modularity of Systems:** The smart factories adapt the changing requirements by expanding or replacing individual modules with respect to the job.

The manufacturing organizations face challenges while implementing Industry 4.0 technologies despite their benefits, as reported in the literature [12,23,28]. These challenges include the limitation of resources, particularly for SMEs, such as finances, knowledge, and awareness of technology [28]. The dynamics of technology adoption differ from the micro to the macro scale of enterprises. The scale of the enterprise makes it difficult to choose the desired technology against required outcome due to abundance of technologies. Similarly, specific challenges were identified by Modrak et al. [29] using a systematic literature survey. In the cluster of production, the use of RFID technology to process data, the use of human-computer interaction, the use of information communication technology for production status identification, and the introduction of the internet of things in production to optimize processes are nominal complex challenges for implementation [6,29]. On the other hand, in the logistics cluster, implementing automatic control systems in delivery operations, the use of robotics in stores, and managing inventory autonomously involve challenges in the

supply chain for the implementation of Industry 4.0 technologies [12,17,29]. Furthermore, from the organizational and managerial perspective [30], providing the mass customization of products to customers and their organizational models make the implementation of Industry 4.0 complex. However, the health crisis has made us think in a way to solve specific challenges through a handful of technologies' implementation. This research study helps at a strategic level through the prioritization of the root cause challenges, and helps to propose the implementation of their possible remedial Industry 4.0 technology.

The technologies potentially roadmap a success journey in the business world. The only challenge lies in implementing the right technology to solve a specific challenge. This study helps is crafting the way out of this challenge. The implementation of the technologies helps us achieving the following outcomes in the time of pandemics [8,12,14].

1. Rapidly recover revenue.
2. Rebuild operations.
3. Rethink the organization.
4. Accelerate digital adoption to enable reimagination.

#### 1.2.2. Potential Benefits of Using Industry 4.0 Technologies during COVID-19

The benefits associated with Industry 4.0 technologies range from facilitation in the business operations through cloud computing and autonomous robotics [18] to providing aid to the government by meeting medical demand through flexible and additive manufacturing [19]. A brief insight of the benefits associated with these technologies is provided in Table 1.

**Table 1.** Industry 4.0 technologies, their brief description, and potential benefits amid pandemics.

Sr. No.	Industry 4.0 Technologies	Brief Introduction	Potential Benefits in the Pandemic	Ref.
1	Autonomous robotics	<ul style="list-style-type: none"> <li>• Joint technology of artificial intelligence and robotics to take decisions and carry out assignments</li> <li>• Collaborative robotics to ensure social distancing</li> <li>• Ethically fit for industry-based applications in unsafe circumstances</li> <li>• Improved flexibility and a step towards sustainable production and other operations</li> </ul>	In the times of COVID-19 pandemic, robots could be used to serve medication to patients, to affirm that people are maintaining social distancing, in industries perform repetitive tasks to create an environment of collaborative workplace and assist in logistical activities in hospitals as well as in industries.	[18,22]
2	Big data analytics	<ul style="list-style-type: none"> <li>• Pattern recognition and information extraction from internet of things-based equipment</li> <li>• Trackability and traceability to have more control on production and product with customer</li> <li>• Efficient resource utilization and optimization</li> <li>• Instances to train AI-based models for effective decision making</li> <li>• Processing of large-scale customer and product data for ethical and sustainable operations</li> </ul>	During pandemic like situations, analytics based on big data helps to analyze and forecast the impacts of disease on people and supply chains. Moreover, it helps in tracking and collecting the real time data which equips medical practitioners, businessmen, analysts, and other personnel. In addition to this, it also improves the policy deployment through sentiment analysis of response of public as well as provides efficient transparency to business and supply chain networks.	[22,31]

Table 1. Cont.

Sr. No.	Industry 4.0 Technologies	Brief Introduction	Potential Benefits in the Pandemic	Ref.
3	System integration	<ul style="list-style-type: none"> <li>• Cyber physical systems to improve resource utilization and integrated system performance</li> <li>• Comprehensible human-system interaction for decision making in physical environment to achieve operations sustainability</li> <li>• Digital twin to aid in autonomous decision making and safer experiments on system</li> </ul>	<p>Systems integration across different departments backed by artificial intelligence can help in predicting and minimizing the spread of disease. Moreover, it helps to navigate and take down wrong news to refrain the public from panic. Also, the trail phase could be systemized and helped by creating virtual support through investigating medicine effects on tangible implants and analyzing them across the system. Moreover, the merger of physical world, robots, and simulation based virtual environment can help in analyzing more critical situations. It also helps in manufacturing healthcare related equipment at the time of need. Internet of things is helping by providing drone-based surveillance, mask detection and wearing enforcement, segregating affected ones from business and other operations places and helping medical practitioners through diagnosing the disease. It helps industries by keeping social distancing between employees, partially automating the work, and providing the safe and secure operations environment. Moreover, it helps the medical teams in relief operations to monitor patients remotely and provide them medication.</p>	[13,18,23,32]
4	Internet of things	<ul style="list-style-type: none"> <li>• Data gathering from devices integrated with internet related to efficiency, machine usage and energy consumption for cost-based optimization</li> <li>• Reliable systems to ensure sustainability of system and ethical considerations</li> <li>• Monitoring of physical- and e-waste, machine and product life cycle</li> <li>• Enormous transition to automated systems and data collection from sensors sent to cloud for analytics</li> </ul>	<p>Flexible manufacturing can help in large scale production of essentially required items during pandemics. It happens to support governments through modern technologies such as virtual reality, robots, flexible systems, and industrial designing capabilities. In addition, the systems are backed with the sensors such as biosensor in the time of health crisis (providing essential regulatory measures). These help in carrying out mass production without any hindrance through easily employable, sensitive, and economic support.</p>	[13,23,31]
5	Flexible manufacturing	<ul style="list-style-type: none"> <li>• Decreased lead time and improved productivity</li> <li>• Efficient resource utilization with decreased energy utilization to achieve sustainability in business operations</li> </ul>		[19,23,31]

Table 1. Cont.

Sr. No.	Industry 4.0 Technologies	Brief Introduction	Potential Benefits in the Pandemic	Ref.
6	Augmented reality	<ul style="list-style-type: none"> <li>Improved flexibility, efficiency, and reliability in completing high-tech jobs by an average skilled worker</li> <li>Integration of human-machine interaction with digital environment</li> <li>Improved training simulations with the experience of reality without substituting environment</li> <li>Increased comfort and productivity; through holography, changing performance environments and reconstruction of actual procedure to enhance reliable execution</li> </ul>	<p>The technologies of virtual and AR integrate remote groups working on specific tasks. The technology can help during pandemic and lockdown situations when people's safety is important and can be maintained through social distancing. It also increases group's productivity, decreases travelling cost, and consequently, the absenteeism of employees. In addition to above benefits, the technology has also helped in the form of holography. The organization of conferences, meetings, educational activities, and other training sessions for employees, it has helped a lot by providing ultra realistic experience.</p> <p>During the term of social isolation during health crisis, all services and business went online providing services on internet on the place of physical support. The data collected and managed through these industries increased exponentially which put them in another challenge to analyze the dynamic and live data. Similar is the case with the industries, due to rise in automated systems, the data exponentially increased. Therefore, cloud computing technologies can help in analyzing real time data and optimizing the services and operations experience. Similarly, the data obtained from various hospitals related to disease diagnostic can also be analyzed remotely and transferred to other units for further processing.</p>	[23,33,34]
7	Cloud computing	<ul style="list-style-type: none"> <li>Highly transparent and responsive system</li> <li>Enhanced data sharing and improved communication among SC stakeholders</li> <li>Increased level of monitoring for sustainable operations to ensure viability in tough times</li> <li>Increased opportunities to upgrade technology</li> <li>Improved reliability through cloud data access, reduction in running cost and improved effectiveness</li> </ul>	<p>During the term of social isolation during health crisis, all services and business went online providing services on internet on the place of physical support. The data collected and managed through these industries increased exponentially which put them in another challenge to analyze the dynamic and live data. Similar is the case with the industries, due to rise in automated systems, the data exponentially increased. Therefore, cloud computing technologies can help in analyzing real time data and optimizing the services and operations experience. Similarly, the data obtained from various hospitals related to disease diagnostic can also be analyzed remotely and transferred to other units for further processing.</p>	[13,22,35]
8	Additive manufacturing	<ul style="list-style-type: none"> <li>Reduced degree of waste (material and environmental)</li> <li>High flexibility and consistency to produce complex geometric designs</li> <li>Cost-effective and improved validity tests of prototypes</li> <li>Increased affordability of manufactured parts</li> <li>Increased help in concurrent engineered product to market through improved throughput rate</li> </ul>	<p>The additive manufacturing also known as 3D printing can be employed in critically unprecedented conditions. This technology can help in manufacturing the medical aids, providing mass production of surgical masks and ventilator parts, producing medicines, and printing human implants.</p>	[19,31,36]



## 2. Research Problem and Objectives

Business tycoons are struggling to implement technologies to address the global business challenges which emerge due to disrupting situations like the pandemic. Moreover, the adoption of modern technologies was gradual in small and medium enterprises (SMEs), which cover the most of manufacturing sectors (95% in India, 90% in Europe) [28,36]. Due to the highly competitive business market, industries look forward to an upsurge in the efforts in technical deficiency, sustainability in business operations, and their reliability. This global, unmatched challenge has put strain on the manufacturing sector because of the lack of realization of sustainable business criteria [14,17].

Because of the emerging business sustainability problems because of COVID-19, industries are encountering challenges while managing their SCs and business operations because of ineffective strategies [5]. The business dynamics during a health crisis face challenges like low system flexibility [37], a mismatch between supply and demand, and the inadequate viability of SC networks [13,17,38]. Therefore, to address these problems effectively, there is potentially a high requirement to analyze COVID-19-induced challenges under the paradigm of sustainability. The scarcity of the studies on the selected domain highlights the urgent need to analyze COVID-19-induced challenges and the potentiality of Industry 4.0 technologies to assist SMEs and larger enterprises in these tough conditions. The current research aims to investigate the potentiality of Industry 4.0 technologies to solve the COVID-19 challenges for long-term sustainability.

Survivability, efficiency and business operations sustainability can be ensured through technology adoption [8]. The journey towards efficiency and sustainability is possible through process and operations digitization through the implementation of Industry 4.0 technologies [12]. Enterprises need to implement state-of-the-art technologies to survive and excel in the current business dynamics. The companies can ensure sustainability in operations by resolving COVID-19-induced challenges at a strategic level with the aid of Industry 4.0 technologies [8]. However, the high cost of sustainability reforms, inadequate standardized and skill metrics, and the inability to adopt promising technologies can hinder the performance and generation of opportunities for sustainability in businesses models [28].

This study investigates the research questions (see Figure 1) in order to help industrial practitioners or leaders to develop or to focus on roadmaps for sustainable future systems. These focused interventions help us to identify the potential challenges in order to form counter strategies in the light of strategic decision making, and also act as decisive support in the Industry 4.0 implementation phase to combat future COVID-19-like disruptions. In this regard, the research study connects the dots in strategic decision roles through the detailed analysis of the chaotic situation caused by the pandemic.

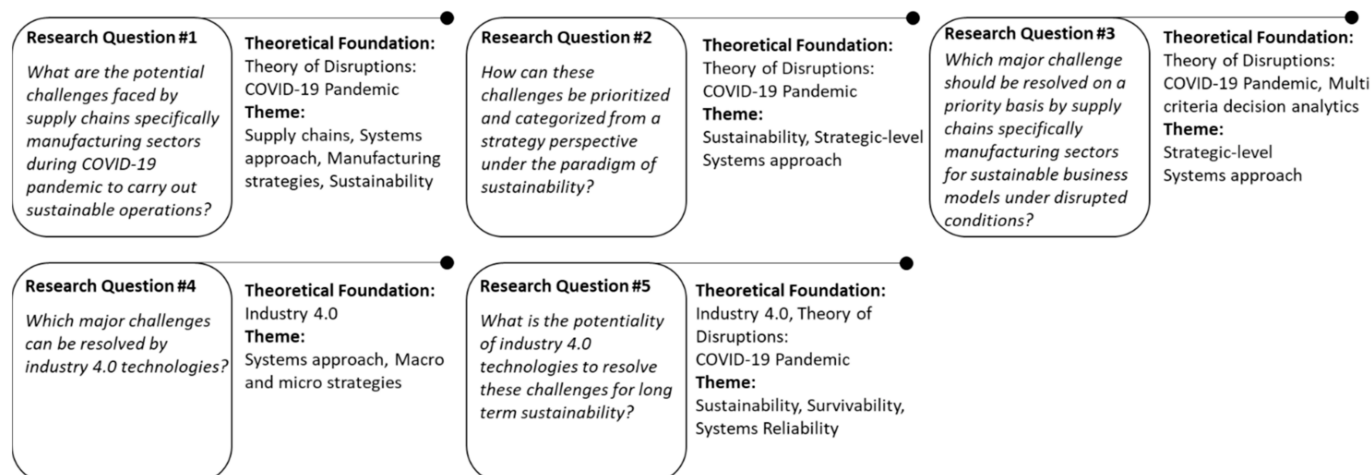


Figure 1. Research questions and their theoretical foundations.

### 3. Methodology

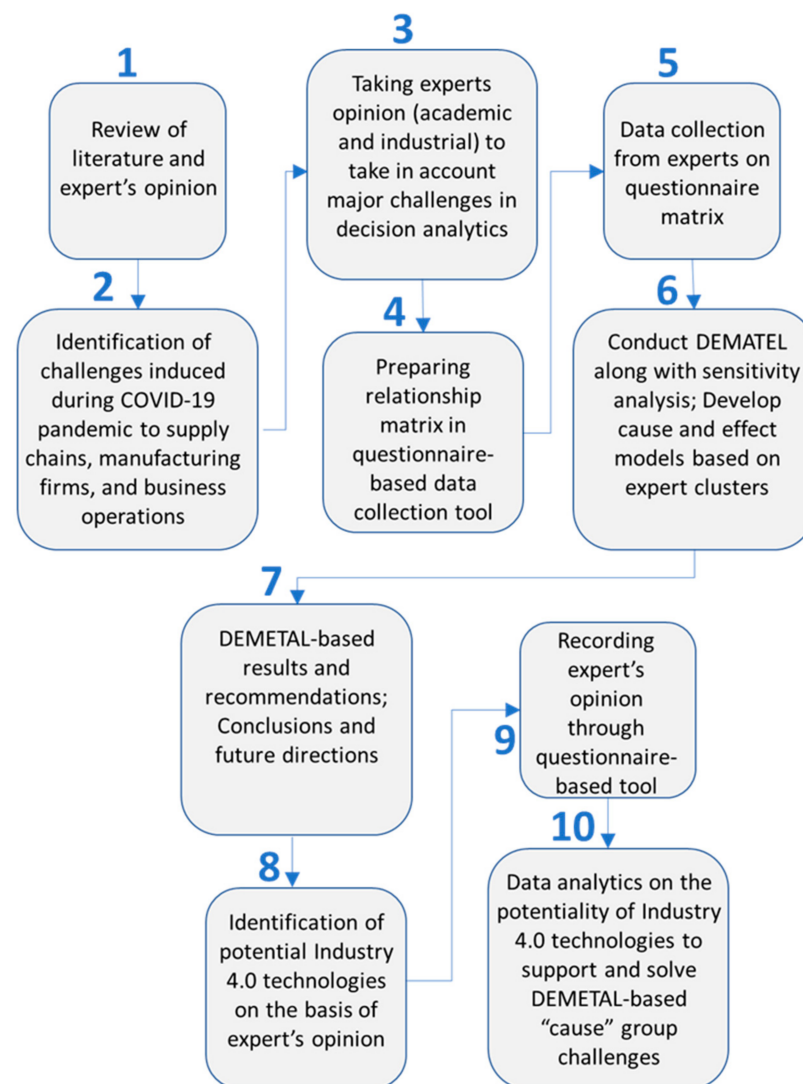
The aim of the paper is the identification of COVID-19's challenges, their prioritization, and the evaluation of the possibility of their solution through Industry 4.0 technologies. Therefore, to identify major challenges, a literature exploration analysis was performed, which helped in forming a master list of the challenges. Then, through an expert panel discussion, the challenges were grouped. The study used an integrated methodology of the Delphi approach (that is, a systematic process used to arrive at a group decision or opinion by surveying a panel of experts) with a Decision-Making Trail and the Evaluation Laboratory (a technique for prioritization and categorization) [39]. With the master list of challenges, the Delphi method invited aggregate opinions from a diverse pool of experts through a meeting. This step was carried out using a virtual conferencing tool instead of a physical meeting. The responses of the experts were kept anonymous, and the individual panelists did not have to worry about the repercussions for their suggestions. The consensus was reached after swaying the information to make it more effective in four rounds.

Firstly, to identify the challenges, a literature exploration analysis was carried out and a master list of challenges was extracted. The list was presented to 22 experts (seven from industry and 15 from academia) as a basic input draft for further exploration, endorsement, and categorization. The questions which were focused on during the Delphi-based activity were: "What are the major challenges caused by COVID-19 to business, manufacturing industries, and supply chains overall in terms of sustainability of operations?" and "How to group common challenges for better decision making and to form a better, refined input for next analysis?". Then, the challenges were revisited, discussed and grouped together to incorporate a strategic roadmap for improvement. The problems identified in the previous sections were systematically investigated through a research model, as showcased in Figure 2. The first step involved a brainstorming session to conceptualize the study on the basis of the experts' opinions. The step 2 involves rigorous literature review and exploratory data analysis process on the basis of what challenges are identified and Delphi method which explored, verified, and grouped as shown in Table 2.

**Table 2.** Prominent challenges affecting supply chains and business operations during the COVID-19 pandemic.

No.	Key Challenge	Brief Narrative	References
1	Low system flexibility	Decreased throughput rate, expanded lead time, inadequate responsiveness to market fluctuations	[12,19,23,36,40]
2	High mismatch between supply and demand	Extremely uncertain demand, decreased logistical activities, delays and supply shortage	[12,17,19,40]
3	Elevated consumer generated bullwhip effects	Customer behavior, increased stockpiling, retailers selling monopoly, retailers, and consumer behavior with factory outlets	[9,17,29]
4	No responsibility and trust issues	Competency and integrity within SC stakeholders, mismatched deliverables, double-crossing under uncertain environments, contactless deliveries between consumers and retailers	[14,17,38,40]
5	Inadequate viability of SC network	Survival during unprecedented circumstances, less resilient systems, low adaptability, inadequate capacity to improve networks to ensure sustainable system	[17,40,41]
6	Poor access to real customer and lack of infrastructure	Inadequate penetration to market and access to information, inefficient logistical infrastructure, unavailability of capacity enhancement and subsequent storage opportunities	[12,17,23,40]
7	Insufficient human resource availability and security	Shortage of labor and emergency medical support, inefficient security protocols for employees to ensure safer work environment and consumers' safety	[12,17,19,23]
8	Unavailability of medical capabilities for safer workplace	Shortages of disinfectants, safety tools and sanitization amenities	[8,31,38,41]
9	Governmental policies and support	Inadequate incentives, insufficient support in logistical activities, lockdowns and enforced restrictions on business retails, no cost-sharing opportunities for special production targets	[6,19,20,38,40]
10	Inadequate system transparency and communication	Openness between SC nodes, miscommunication between organization, governmental authorities, and local bodies	[17,19,33,40]

The Decision-Making Trail and the Evaluation Laboratory technique, termed the DEMATEL technique, is employed in the development of inter-relationships amid COVID-19-induced challenges. The aim leads us to identify the utmost influential ones. In addition to this, sensitivity analyses are performed for verification, durability, and reliability purposes. Step 3 incorporates the data collection tool development and data collection. The relationship matrix based on the responses and its analysis through DEMATEL is carried out in steps 4–6. Step 7 identifies the prime causes of the challenges affecting business the most. Similarly, step 7 incorporates the literature review process and brainstorming session to identify potential Industry 4.0 technologies which may help in these chaotic situations. The recommendations are made based on the opinion of strategic and system experts in step 9 and 10.



**Figure 2.** Research methodology.

The research model covers all of the aspects of the study following the whole project methodology. From a strategic perspective, DEMATEL is a potentially favored technique compared to the analytical hierarchy process, interpretive structural modelling, or any other multi-criteria decision making technique. It mainly divides the decision variables into cause and the effect groups, along with highlighting the ranking of the variants of both groups [37]. This determines the severity and roadmaps the potential of quantified observations for policy makers [38]. The diagraph of challenges highlights the inter-relationship on the scale of 0–4. The technique categorizes all of the factors in order to

formulate effective strategies to solve prioritized challenges. The tool develops the inter-relationship between the challenges. For instance, Kumar et al. [42] used DEMATEL to prioritize Industry 4.0 implementation barriers in small and medium enterprises. On the other hand, [43] classified blockchain success factors. Likewise, many others [44,45] utilized DEMATEL for the analysis of enablers of IoT systems, and the barriers of circular economy and Industry 4.0, respectively. Similarly, Singh et al. [46] implemented DEMATEL for the growth in the Indian food industry through the application of information communication technology. Kumar and Dixit [47] analyzed challenges related to e-waste management. The concise yet detailed methodology of DEMATEL is categorized in Figure 2, and explained in steps.

- Experts' opinions and the calculation of the arithmetic mean direct relationship matrix.

The first step includes collecting experts' opinions for the development of pairwise contextual interrelationship of the identified factors. The opinions are recorded on the scale of 0–4, where 0 indicates “no influence” and 4 is assigned for “very high influence/impact”.

$$X^K = [x_{ij}^K] \quad \text{for } n \times n \text{ matrix of expert } K \quad (3)$$

$$A = [a_{ij}] = \frac{1}{K} \sum_{K=1}^K x_{ij}^K \quad (4)$$

The average-based Direct Relationship Matrix is signified as  $A_{ij}$ .

$$A_{ij} = \begin{bmatrix} a_{11} & \dots & a_{1j} & \dots & a_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{i1} & \dots & a_{ij} & \dots & a_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nj} & \dots & a_{nn} \end{bmatrix} \quad (5)$$

- Normalize the Direct Relation Matrix ( $X$ ).

Normalization is carried out on the obtained average Direct Relationship Matrix.

$$X = [X_{ij}]_{n \times n} \quad (6)$$

- Develop the full Direct/Indirect Relationship Matrix.

$$X = z \times A \quad (7)$$

$$\text{where } z = \min \left( \frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n a_{ij}}; \frac{1}{\max_{1 \leq i \leq n} \sum_{i=1}^n a_{ij}} \right) \lim_{h \rightarrow 0} X^h = [0]_{n \times n}, \quad 0 \leq X_{ij} \leq 1 \quad (8)$$

- Calculate the Total Relationship Matrix ( $T$ ).

$$T = X(I - X)^{-1} \quad (9)$$

Here,  $I$  is an  $n \times n$  identity matrix.

- Produce the cause and effect relationship diagram from  $T$ .

After calculating the total relationship matrix, which is termed as  $T$ , the summation of all  $i$ th and  $j$ th rows elements are described as  $D_i$  and  $R_j$ , respectively. To attain the inter-relationship of factors,  $D_i + R_j$  is calculated. Furthermore,  $D_i - R_j$  determines the cause-and-effect relationship of the factors. The positive inferences are indicated as causing factors, whereas the negative inferences are reflected as effects.

## 4. Analysis and Discussion

### 4.1. Delphi-Based Identification of the Challenges

The base list was provided to the group of experts, and the exploration of the COVID-induced challenges was carried out using their personal opinions, experience, and/or previous research. The information was scrutinized and compiled for the next round of discussion. The final consensus was reached, and the challenges were grouped to represent the holistic situation. Several key challenges are presented, which affected supply chains, manufacturing systems and business operations during the COVID-19 pandemic, and are mentioned in Table 2. The challenges at the production level are related to the decreased throughput rate, increased lead time of products, and inadequate responsiveness to market fluctuations. Similarly, the inadequate viability of the SC network, poor access to real customers, and the lack of infrastructure were termed to be difficult positions for the manufacturers and retailers. In addition, various challenge groups are presented after the unanimous consensus of the experts, and are shown in Table 2.

### 4.2. DEMATEL-Based Analysis of Challenges

An expert panel was called to extract the potential challenges from the literature exploration analysis, and to analyze the impacts of COVID-19 challenges on one another. The academic (professors/associate professors of relevant research interests and expertise) and industrial experts (advanced manufacturing systems and technology experts in business operations perspective having at least 10 years' experience) were selected as respondents of the project. In addition, the industrial experts were scientists working on the research and development of Industry 4.0 technologies, practitioners implementing the technologies on the ground, and strategic decision makers such as technology officers, managers, and directors. The industrial experts were from leading organizations such as Siemens; Apple; General Electric, UNIDO; Saudi Aramco; Appen and others. Similarly, the academic experts were selected from Hong Kong University; KAIST; the University of Strathclyde; the University of Cambridge; Lahore University of Management Sciences (LUMS); the University of Engineering and Technology, Lahore; Imperial College London; Tsinghua University, and others. The questionnaire was deployed to record the interrelationship of the challenges and the potential of Industry 4.0 technologies to solve the cause-group challenges. The experts from industry were at managerial positions or above, and the academic experts had a PhD as their minimum qualification, and all had the purpose and aims of the study explained to them. The explanation further included a brief insight on the technologies' and challenges' details. In total, 35 experts (15 from industry and 20 from academia) responded to the questionnaire (see details in Table A1). The mode of communication for correspondence was through online video meetings, emails, and sometimes in-person visits. In order to improve the response rate (~70%), adequate time and frequent reminders were ensured. The integrity of the responses was ensured through reliable data collection sources.

For DEMATEL-based calculations (Equations (3)–(9)), the very first step is to develop an arithmetic mean matrix of the responses, termed the Direct Relationship Matrix (see Table 3).

The matrix was further normalized in the range of 0 to 1, as evidenced in Table 4. The normalization was carried out in order to change the numeric values on a common scale without distorting the range of the dataset. Furthermore, it is not always necessary for every dataset, but is preferred for related analyses. There is primarily no influence of any challenge on itself; therefore, the diagonal of the matrix displays zero impact.

**Table 3.** Average direct relationship matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0	3	2	1.5	1	2	0.5	0.5	0.5	1.5
C2	1.67	0	3	2	1	1	1.5	0.5	0.5	1
C3	2.33	2	0	1	1	1.5	1	1	0.5	0.5
C4	1.33	1.67	2	0	1.5	1.5	0.5	1	0.5	0.5
C5	1.33	2.33	2.33	1.5	0	2.5	2	1	1	1
C6	2	3	2	2.67	2	0	2.5	3	0.5	2.5
C7	1.33	2.67	1.67	2.67	2	1.33	0	1	0.5	1.5
C8	0.67	0.33	1	1	1.67	1.33	2	0	2	2
C9	1	1.67	1.67	1.67	1.33	2.67	2	3	0	2
C10	1	1.67	1.33	1.67	2	2.67	2	1	1.33	0

**Table 4.** Normalized direct relationship matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0	0.148	0.099	0.074	0.049	0.099	0.024	0.024	0.024	0.074
C2	0.082	0	0.148	0.099	0.049	0.049	0.074	0.024	0.024	0.049
C3	0.115	0.099	0	0.049	0.049	0.074	0.049	0.049	0.024	0.024
C4	0.065	0.082	0.099	0	0.074	0.074	0.024	0.049	0.024	0.024
C5	0.065	0.115	0.115	0.074	0	0.123	0.099	0.049	0.049	0.049
C6	0.099	0.148	0.099	0.132	0.099	0	0.123	0.148	0.024	0.123
C7	0.065	0.132	0.082	0.132	0.099	0.065	0	0.049	0.024	0.074
C8	0.033	0.016	0.049	0.049	0.082	0.065	0.099	0	0.099	0.099
C9	0.049	0.082	0.082	0.082	0.065	0.132	0.099	0.148	0	0.099
C10	0.049	0.082	0.065	0.082	0.099	0.132	0.099	0.049	0.065	0

Through Equation (9), the Total Relationship Matrix was calculated, as tabulated in Table 5. The matrix was calculated on the analogy of Equation (9). It helped in processing the numeric values to further classify them based on their inter-relationship. On the basis of their relationships, these variables will be categorized, and their impact will be calculated.

**Table 5.** Total relationship matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0.136	0.317	0.267	0.225	0.178	0.243	0.159	0.136	0.092	0.186
C2	0.206	0.175	0.297	0.236	0.170	0.192	0.190	0.128	0.088	0.154
C3	0.223	0.253	0.152	0.184	0.161	0.202	0.162	0.143	0.084	0.130
C4	0.177	0.231	0.238	0.130	0.179	0.199	0.138	0.141	0.083	0.124
C5	0.225	0.327	0.313	0.259	0.159	0.296	0.253	0.185	0.130	0.191
C6	0.293	0.410	0.355	0.359	0.297	0.237	0.320	0.302	0.138	0.295
C7	0.215	0.328	0.276	0.298	0.241	0.238	0.151	0.171	0.104	0.201
C8	0.163	0.202	0.216	0.206	0.214	0.224	0.233	0.121	0.167	0.216
C9	0.226	0.321	0.307	0.291	0.248	0.332	0.282	0.295	0.102	0.260
C10	0.208	0.299	0.270	0.268	0.253	0.307	0.257	0.189	0.146	0.146

Similarly,  $D_i$ ,  $R_j$ ,  $D_i - R_j$ , and  $D_i + R_j$  were calculated as per the methodological steps, and are listed in Table 6. The multi-criteria decision making method is widely employed to assess security risk control in information systems, portfolio investment prioritization, the digital-twin based effects analysis of systems, knowledge-management-systems, strategy-development and the technology-innovation capability of systems [48]. This wide range of applications is because of the potentiality of the method to categorize and prioritize variables. The final influence analyzed through the quantitative calculations is evident in Table 6.

**Table 6.** The influence ranking of the challenges.

	$D_i$	$R_j$	$D_i - R_j$	$D_i + R_j$	Rank
C1	1.944	2.076	-0.132	4.020	8
C2	1.842	2.867	-1.024	4.709	2
C3	1.698	2.696	-0.997	4.394	4
C4	1.644	2.461	-0.816	4.106	7
C5	2.343	2.104	0.238	4.447	3
C6	3.011	2.475	0.535	5.486	1
C7	2.227	2.151	0.075	4.378	5
C8	1.966	1.816	0.150	3.782	10
C9	2.668	1.138	1.529	3.807	9
C10	2.349	1.908	0.441	4.257	6

Table 7 shows the categorization and prioritization of the challenges in cause-and-effect groups. The value of  $D_i - R_j$  determines the categorization groups, such as the positive magnitude against the cause group and the negative magnitude against the effect group. Table 7 mainly answers research questions 2 and 3. There are two groups in which whole challenges are categorized and also prioritized. For instance, there are six challenges which are accounted as causes, whereas another four are categorized in the effects group. Solving the challenges from the causes group will potentially reduce the effects (challenges induced during COVID-19). Moreover, prioritization is also carried out among these two groups.

**Table 7.** Prioritization and categorization of challenges in strategic perspective.

Challenges as Causes		Challenges as Effects	
Challenge No.	Rank	Challenge No.	Rank
C9	1	C2	1
C6	2	C3	2
C10	3	C4	3
C5	4	C1	4
C8	5		
C7	6		

In the research study, governmental policies and support (C9) to industries, supply chains and businesses critically influenced all of the other challenges, and had the highest positive magnitude (see Table 7). The uppermost value of C9 makes it the most critical in the cause group. Moreover, poor access to real customers to gauge real-time demand and supply requirements, and the lack of infrastructure to fulfill fluctuating needs (C6), inadequate system transparency to access the disturbed node in the network and adequate communication to sustain other operations (C10), the inadequate viability of the SC network against ripple effects causing challenges to survival in the market (C5), the unavailability of medical capabilities for a safer workplace and risking lives of labor (C8), and insufficient human resource availability and security to enhance their confidence in the system (C7) are the second, third, fourth, fifth and sixth challenges which are potential causes of others, respectively.

In addition to the critical causes, the investigation categorized other challenges, such as the high mismatch between supply and demand (C2), elevated consumer-generated bullwhip effects (C3), lack of responsibility and trust issues (C4), and low system flexibility (C1), as the first, second, third and fourth effects, respectively. These insights help strategic decision makers to develop related frameworks to analyze COVID-19-induced challenges, and to find the inter-relationship between other challenges. The casual diagram represents the relations of the challenges with each other in a pictorial manner (see Figure 3). It represents four cases, which group the challenges on both groups differently.

The sensitivity analysis was carried out in order to assess the self-assurance of the optimized solution [49]. It is usually carried out in decision making problems to make the process effective [42,47]. The analysis of challenges is carried out against two decisive conditions. The first is carried out by assigning weights to the challenges, and the second is by changing the assigned weights of each expert group. Rajput and Singh [44] applied the DEMATEL approach to aid in decision making, and performed a sensitivity analysis to verify the hardness of the system. Likewise, [42] changed the weights assigned to the experts for the sensitivity check, and analyzed the cause-and-effect categories. Similarly, Xia et al. [50] performed a sensitivity analysis on analogous terms. The analysis was carried out to verify the biasedness against any group that may lead to compromised results of the research. In this research study, the experts were assigned with equal weights, and the analysis was carried out (see Case 1). The casual diagrams were developed for possible scenarios by allotting two experts a similar weight and one a higher level. This makes three cases, as is evident in Table 8. The calculations are executed, and cause-and-effect categorical rankings are achieved against each case (Case 1 to 4), which are tabulated in Table 9 to designate the consistency of the results. No significant variation in the findings against the varying terms authorize the robustness and hardness of the model. Poor access to real customers and the lack of infrastructure (C6) appears to be most concerning and critical among the others, as verified in the sensitivity analytics (see Table 9).

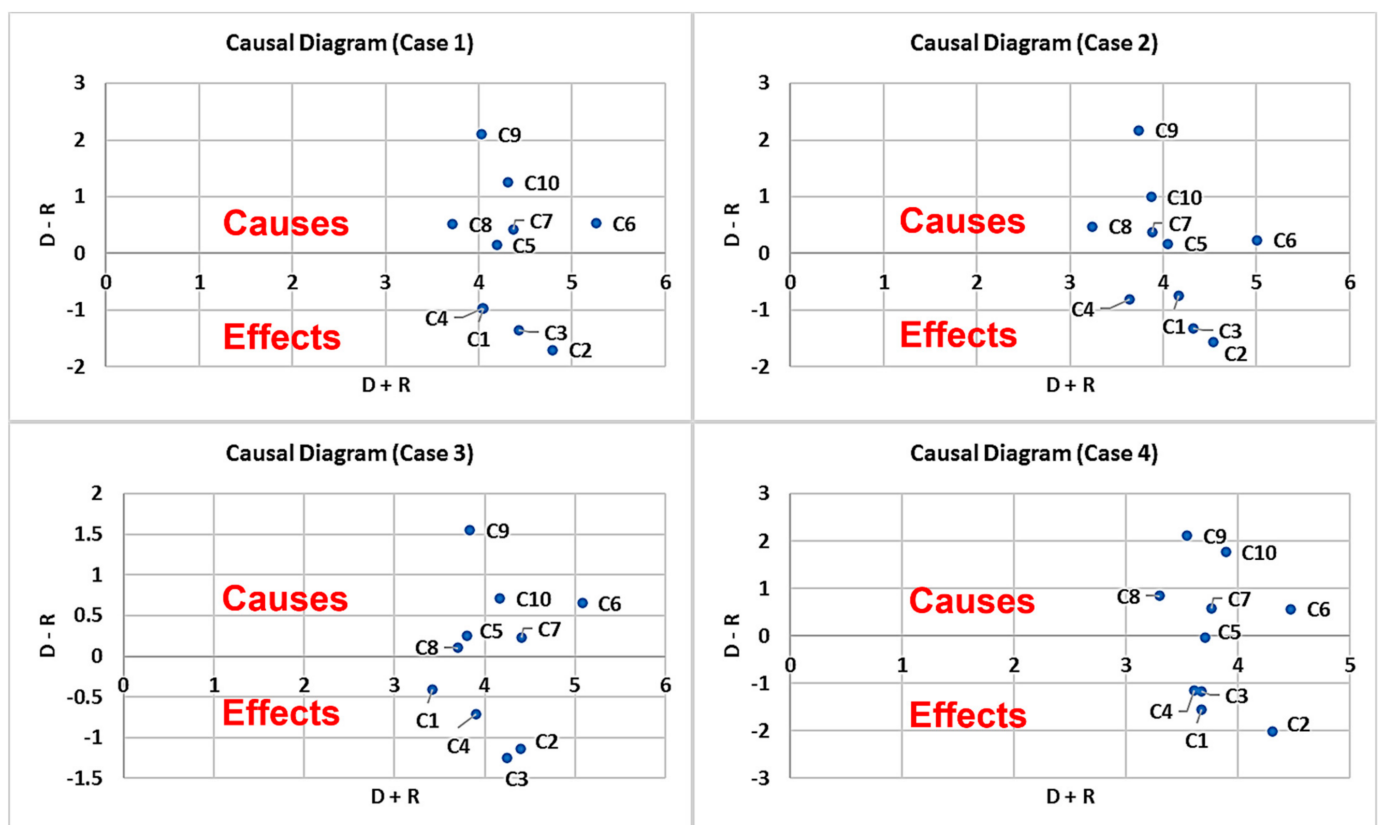


Figure 3. Casual diagrams of cases against the sensitivity analyses.

Table 8. Sensitivity analyses’ criterion and expert weightage.

	Case 1	Case 2	Case 3	Case 4
Expert 1	0.33	0.25	0.25	0.50
Expert 2	0.33	0.25	0.50	0.25
Expert 3	0.33	0.50	0.25	0.25



As per Section 4, the Industry 4.0 technologies which have the potential to support industrial systems are identified. These technologies, if implemented, can resolve multiple challenges and equip our existing systems to become resilient against future shocks and ripple effects [9,16]. As the quantitative results in Section 4.2 display, governmental policies and support towards manufacturing industries, business operations and overall supply chains is the root cause to augment criticalities for sustainable operations. The extracted potential challenges faced by supply chains, and specifically manufacturing sectors, during the COVID-19 pandemic are the baseline for improvement. These challenges are to be solved to make the overall system reliable, sustainable, and efficient in tough times. The challenges, which are the prime area of concern, are shown in Table 2. The decreased throughput rate of industries, along with the expanded lead time and inadequate responsiveness to market fluctuations, resulted in the lowering of the flexibility of the system [23,51]. Moreover, this caused a high mismatch between the supply and demand of essential living products [52,53]. This shortage was caused by extremely uncertain demand, decreased logistical activities, and delays and supply shortage. In addition, customer behavior, increased stockpiling, retailers' selling monopolies, retailers, and consumer behavior with factory outlets further made the situation complex [13]. Conclusively, C5, C6, C7, C8, C9, and C10 are categorized in the cause group from the strategic perspective to achieve sustainability. Working and solving root-cause challenges will help to uplift system efficiency and improve reliability for long term sustainability. Similarly, C1, C2, C3, and C4 are listed as members of the effect group. These challenges will be resolved if the cause group is effectively strategized by experts and decision makers. The challenge of governmental policies and support is the most critical, and should be resolved on a priority basis by supply chains to achieve sustainability in business models under disrupted conditions [54,55].

**Table 9.** Sensitivity analysis-based ranking results.

Challenge No.	Case 1		Case 2		Case 3		Case 4	
	$D_i+R_j$	Rank	$D_i+R_j$	Rank	$D_i+R_j$	Rank	$D_i+R_j$	Rank
C1	4.020	8	4.120	4	3.416	10	3.674	6
C2	4.709	2	4.497	2	4.396	3	4.308	2
C3	4.394	4	4.276	3	4.251	4	3.673	7
C4	4.106	7	3.598	9	3.900	6	3.608	8
C5	4.447	3	4.025	5	3.806	8	3.705	5
<b>C6</b>	<b>5.486</b>	<b>1</b>	<b>4.956</b>	<b>1</b>	<b>5.079</b>	<b>1</b>	<b>4.471</b>	<b>1</b>
C7	4.378	5	3.834	7	4.409	2	3.766	4
C8	3.782	10	3.215	10	3.701	9	3.299	10
C9	3.807	9	3.703	8	3.831	7	3.541	9
C10	4.257	6	3.836	6	4.171	5	3.892	3

The sensitivity analysis resulted in no substantial variance of findings under varying conditions. The robustness and reliability of the model is indicated in Table 9 and Figure 3. The key findings from the casual diagram show that governmental policies, the inability to access real customer requirements, and the high mismatch between supply and demand are the important challenges which have made the industries think for survival of their operations for sustainability goals. Furthermore, competency and integrity within SC stakeholders may save businesses from mismatched deliverables or double-crossing in uncertain environments. The possibilities of failure in the continuation of business operations extend if these key challenges are ignored. These challenges could potentially be solved through modern promising Industry 4.0 technologies [8,12,13]. The ranking of the challenges against each group indicates the critically and required amount of focus from industrial tycoons, governments, business operations managers, leaders, and other policy makers [51]. Therefore, the overcoming strategies need to be devised with the help of Industry 4.0 technologies, which will not only solve the current COVID-19 pandemic's tough

situations but also will potentially improve the reliability of business operations against future disasters, pandemics, epidemic outbreaks and their respective ripple effects [1,9].

#### 4.3. Domain-Oriented Insights

##### 4.3.1. Strategic-Level Supply Chain Experts

In this section, the direct potential of Industry 4.0 technologies to solve COVID-19-induced challenges was mapped by experts who were involved in strategic decision making in supply chains and related business operations (see Figure 4). As per the strategic decisive roles, big data analytics backed by cloud computing, and the internet of things will hypothetically increase resilience and adaptability, and enhance the capacity and security of networks, solving C5 [55–58]. Furthermore, big data analytics can possibly provide adequate penetration to the market and access to information [22]. This technology can help improve logistical infrastructure and reduce inventory-management-related problems (C6). Similarly to C6, C7 could be resolved through big data to enhance security- and safety-related protocols for employees [57]. Cloud computing, along with the internet of things, will help to deal with the shortages of disinfectants, safety tools and sanitization amenities by providing flexible and adaptable production operations and the realization of actual requirement (C8) [19,41,58,59]. Cloud computing helps to strategize information and optimize policies. This further helps in collaboration with big data analytics to provide additional support in logistical activities and the easing down of the enforced restrictions on business retails (C9) [56]. Big data analytics depicts the true picture of demand from actual customers and the internet of things to communicate the possible numbers of products being manufactured by systems (C10) [12,46,60]. These technologies (majorly big data analytics, the internet of things, and system integration) help to solve the most critical challenge related to governmental policies via the improvement of communication between stakeholders, and by enhancing the true depiction of systems.

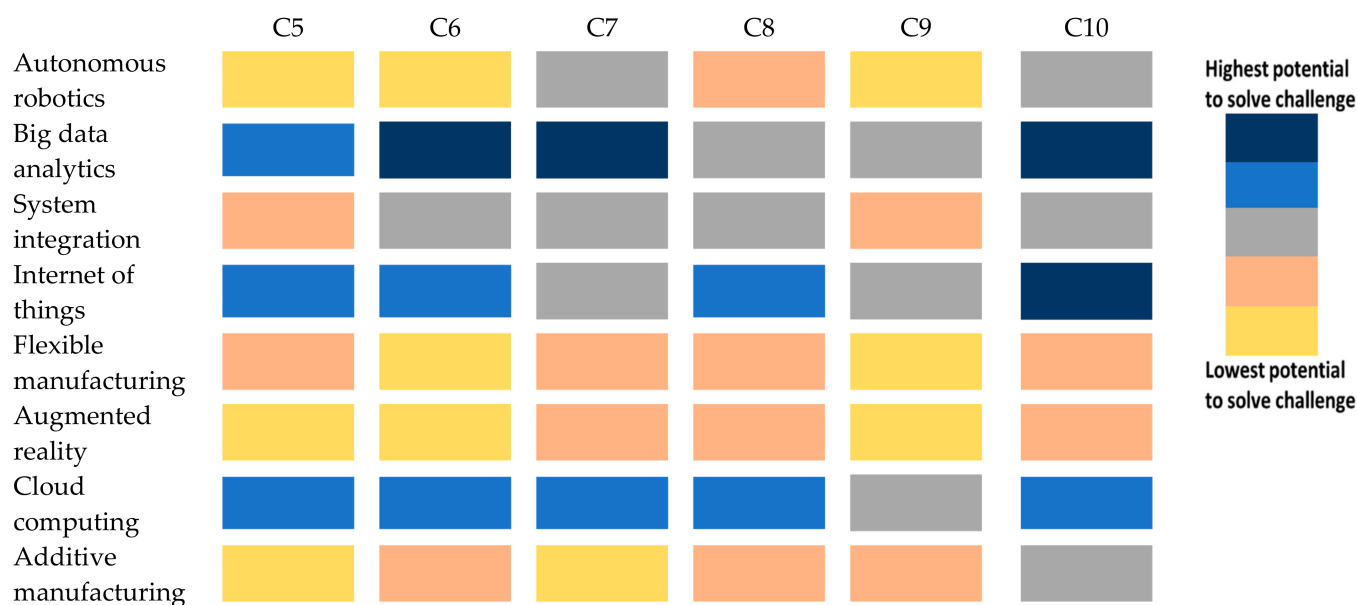


Figure 4. Industry 4.0 technologies to solve COVID-19-induced challenges from strategic experts' perspectives.

##### 4.3.2. Industry 4.0 and Industrial Systems Experts

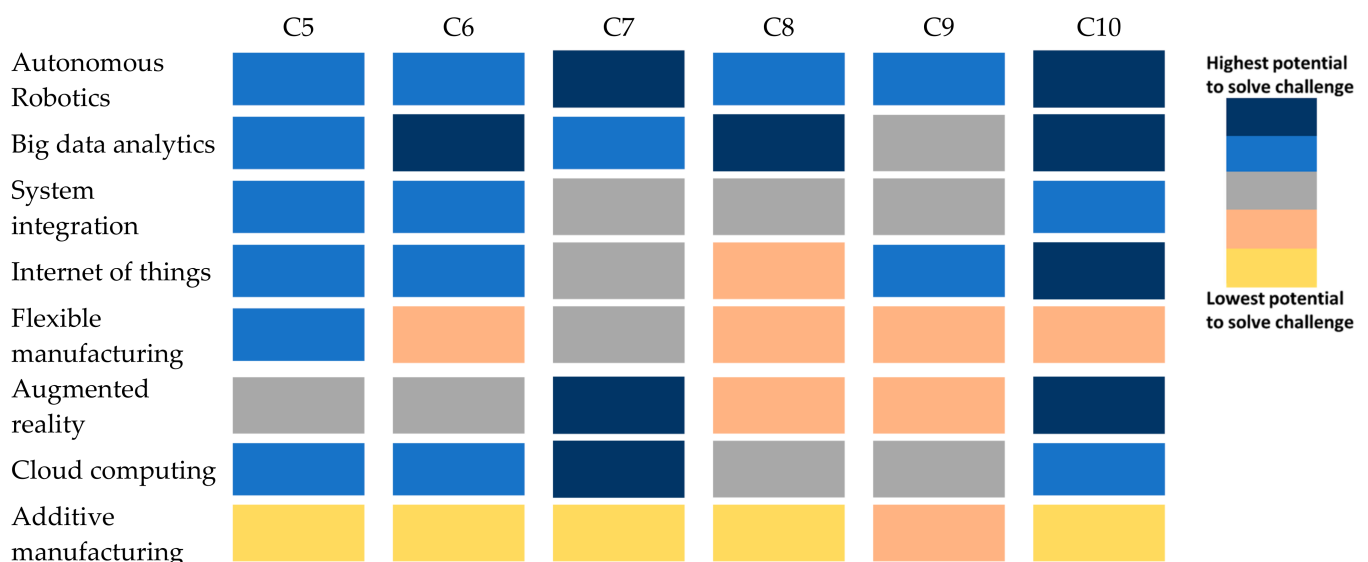
This section maps Industry 4.0 and industrial systems experts' points of view regarding modern technologies to solve cause-group business challenges related to COVID-19, in order to aim for a sustainable environment (see Figure 5). Big data analytics can help to control survival during unprecedented circumstances. Moreover, system integration will improve the resilience of systems [61] and increase adaptability. The internet of things, along with flexible manufacturing, can enhance the capacity to progress networks to en-

sure a sustainable system [62]. These four technologies can potentially be of benefit in circumstances like C5 [12,23,63]. Similarly to strategic decision makers, industrial system experts see eye to eye to solve the penetration to the market and access to information challenges through big-data analytics (C6). AR backed by cloud computing can reduce the shortage of labor and provide emergency medical support [34]. It will aid autonomous robotics to enhance the efficiency of security protocols for employees to ensure a safer work environment and consumers' safety (C7) [18,64,65].

As per the Industry 4.0 technical experts, big data analytics will dig into production and demand information generated through industries and demand centers to lower the shortages of disinfectants and related sanitization amenities (C8) [22,57]. Similarly to the guidelines by supply chain experts, the internet of things and big data analytics can help for transitioning labor-related incentives, providing cost-sharing opportunities for special production targets and help in logistics management (C9) [58,66]. Autonomous robotics controlling operations in a significant ratio, backed by the internet of things, can improve the communication of product supply and quality-related details to higher management.

"Industry 4.0 facilitates horizontal and vertical digital information flow along value chains up to the end-customer and is highly relevant in a broad variety of industries" [67]. "AR is a key technology in Industry 4.0, which connects the virtual and real-world environments using such digital information flows" [67]. AR helps to enhance the openness between SC nodes and related business operations in various business sectors (C10). Although AR has associated benefits, significant challenges still exist which may also be associated with AR's success, as measured through various implementation success factors, e.g., user acceptance, system configuration and organizational fit [32,67–69]. AR\* frameworks based on success factors and metrics of photonic components may be considered while designing and developing light-based hardware to be used for AR systems [67].

Big data analytics help governmental authorities and local bodies to lower miscommunication between organizations [22]. Thus, it is accepted by experts that various Industry 4.0 technologies may potentially help in addressing cause-group (global) challenges in order to achieve long-term sustainability [70].



**Figure 5.** Industry 4.0 technologies to work out COVID-19-induced challenges, from systems technical experts' viewpoints.

## 5. Conclusions and Related Implications

The world has been facing an unprecedented pandemic, COVID-19, which has affected businesses that are the backbones of economies severely. Manufacturing giants and other business operations are important parts of GDPs which compete globally, having ethically sustainable and efficient operations. These operations support economies and provide a

living to large communities. A number of studies reported unavoidable challenges cause by COVID-19 which made business owners think about operational survival. The survivability and sustainability of micro- to large-scale enterprises became challenging. These challenging conditions are grouped into 10 major challenges which affected businesses in comparable ratios. The analysis was made to rank and categorize the challenges using the DEMATEL decision-making technique. Governmental policies and support popped up through the calculations as the greatest critical challenge in the cause group. Moreover, the high mismatch between supply and demand was found to be the utmost notable effect in the effects category. The challenges in the cause group are influential on the effect group; therefore, additional focus is required while prioritizing the strategic plans and frameworks. Moreover, the cause-group challenges were further analyzed by experts to rate the potentiality of Industry 4.0 technologies to help against each influential challenge. Finally, the implementation of a specific technology to resolve any challenge can lower the risk of system breakdown during future shocks. The possible answers to the research questions are stated in Table 10.

**Table 10.** Reference to the findings of the research.

Research Question	Reference	
RQ 1	What are the potential challenges faced by supply chains specifically manufacturing sectors during COVID-19 pandemic to carry out sustainable operations?	The output of Delphi approach stated in Table 2 highlights the potential challenges.
RQ 2	How can these challenges be prioritized and categorized from a strategy perspective under the paradigm of sustainability?	The DEMATEL analysis prioritized and categorized the said challenges as termed in Table 7.
RQ 3	Which major challenge should be resolved on a priority basis by supply chains specifically manufacturing sectors for sustainable business models under disrupted conditions?	The ranking shown in Table 9 demonstrates the major challenge. The sensitivity analysis results C6 to be the major challenge in said perspective.
RQ 4	Which major challenges can be resolved by industry 4.0 technologies?	The causal group formed through DEMATEL analysis are the most prioritized challenges which need immediate focus and evaluation through Industry 4.0 lens as illustrated in Figure 3.
RQ 5	What is the potentiality of industry 4.0 technologies to resolve these challenges for long term sustainability?	The output of Domain-experts focus on the potentiality of technologies to resolve the selected challenges as shown in Figures 4 and 5.

### 5.1. Empirical and Theoretical Implications

The Industry 4.0 technical and strategic decision makers' approach towards solving modern world challenges is integrated to form a joint framework for improvement. The empirical evidence of the opinions of these experts counts government policies and support to be the top-ranked challenge which significantly affects the other problems (the  $D_i - R_j$  value is 1.529). Moreover, poor access to real customers and lack of infrastructure is the second most important challenge ( $D_i - R_j$  value to be 0.535). These challenges could be resolved by the implementation of big data analytics for systems with internet of things systems. Empirically, managing and controlling these top two challenges in the cause group will help to reduce the impact of other, related challenges. In addition, based on the results, strategic decision makers should give more weight to these challenges while devising industrial frameworks for the sustainability goal. Furthermore, Sheng et al. [22] worked to develop an intelligent manufacturing framework to help in situations like pandemics. The aim of the research was to delve into the influence of COVID-19 challenges on each other when affecting businesses and support management. The study contributes through the elucidation of the theoretical growth of the COVID-19 challenges which contributed equally to economic, social and technology-related avenues. The findings of this study make a significant contribution to the knowledge base regarding the impacts of COVID-19.

The prominent findings include the identification of the challenges caused by COVID-19 to businesses and supply chains, and their grouping for quantitative analysis. Moreover, we also completed the categorization and prioritization of these challenges to identify the crucial ones. Finally, we evaluated the potentiality of Industry 4.0 technologies to solve those critical challenges. The results show that resolving prime challenges and understanding the productive relationship between them needs strategic decisions to be taken relating to Industry 4.0 technologies' implementation. This will help to control short- and long-term threats of survivability breakdown. In order to excel in the international market, the implementation of specific technologies (big data analytics, the internet of things, autonomous robotics) will help to reduce the impacts of the pandemic on global supply chains, and will also improve the resilience and competitiveness of business models. Regarding the cause and effect challenges, if solved on time with the adoption of the recommended technologies, this will help us to improve risk preparedness, mitigate the negative impacts, and recover towards operations.

### *5.2. Managerial Implications*

The research will add value to managers' decision-making capacity when they have an interest in the adoption of proactive approaches by understanding the strategies to resolve unprecedented challenges. This pandemic situation is a novel business situation due to the need to meet extraordinary supply and demand requirements, and it needs the development of sustainable business operations practices. This has led towards the transition of economic activities, business operations and societal values. The challenges caused by COVID-19 have taught practical lessons for the adoption of Industry 4.0 technologies as a need of existing business models. The proposition is important to analyze for the mitigation of COVID-19 challenges. The managers need to be proactive and thoughtful regarding novel technologies and strategies, and the modification of plans on various fronts. The managers who are involved in strategic decision-making roles gain practical comprehensions through the above propositions and analyses of challenges. These insights help in reforming economic, social and technology-related concerns. Usually, businesses are very much concerned with short-term goals, but the unmatched situation demands more. Moreover, managers can frame the pathways to get out of the crisis through the proper implementation of Industry 4.0 technologies [37]. They can improve the knowledge base and expertise in the field. The challenges help us to predict the requirement of technology implementation to achieve a resilient, agile, changeable and efficient growth trajectory in the times of pandemics [71,72]. This will also help managers in resource optimization, operations sustainability, and becoming more responsive to fluctuating market needs.

### *5.3. Ecological and Social Implications*

The ecological implications of the research are related to the effective use of Industry 4.0 technologies for business continuity. The efficient use of technologies such as autonomous robotics, energy-efficient systems, optimized solutions and the enhanced performance of production systems will not only help in reducing carbon emissions and improving ecological protocols but also enhance the commitment towards the planet. In addition, an optimized and balanced workplace integrated with Industry 4.0 technologies can help to ensure smooth production under the deployment of the national health council guidelines of workers.

The economic pressure because of COVID-19 on businesses, communities, and governments needs strategic policies and support from the government and other organizations. The support should be skewed towards individuals, businesses, and low-income countries. Appropriately designed policies reform the disturbed situations and play a crucial role in formulating plans for survivability and sustainability goals. Governments should support businesses and industrial sectors in adopting modern technologies to combat pandemic challenges. The findings of this research demonstrate that government policies and support are prime contributors leading to other challenges which are directly

influenced in economic terms. The support and implementation of relevant Industry 4.0 technologies will improve the confidence in the system of the public, maintaining political, social, and economic stability. Moreover, the guidelines recommended by this study can help strategic policy and decision-makers to combat future crises in a better manner. This will be possible through redefining industrial rules and regulations, improving subsidies to increase industrial 4.0 technologies' implementation, and enhancing value chain network reliability. These reforms could be integrated to resolve other medical-related challenges and help restore services, for instance tourism, trade, daily-wage labor employability, and the educational sector.

The research study is limited to the collection of data through literature-based information extraction and quantitative questionnaires. Additional research opportunities could include qualitatively based focus group discussions. Moreover, the overlap of challenges of the COVID-19 pandemic and their solution approach through current technologies with the challenges of previous epidemic outbreaks and their solution methodologies could be compared in order to extend the current body of knowledge in this important domain. However, the region or industry-specific research direction of the current research problem could be a potential direction for research extension.

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## Appendix A

**Table A1.** Summary of the participants' expertise and affiliations.

Participant ID	Expertise	Current Affiliation
ID-1	Workplace design, lean and green production	UET Lahore, Pakistan
ID-2	Engineering management	UET Lahore, Pakistan
ID-3	Supply chain management, network design, sustainability	UET Lahore, Pakistan
ID-4	Industry 4.0, resilience	University of Strathclyde, UK
ID-5	Robotics and automation, Industry 4.0, digital twins	Siemens Energy, Denmark
ID-6	Sustainable manufacturing, industrial automation	Shandong University, China
ID-7	Scheduling in Industry 4.0	University of Lahore, Islamabad
ID-8	Industrial sensors, energy	Tianjin University, China
ID-9	Supply chain management, network design, sustainability	NUST, Islamabad
ID-10	Lean production in Industry 4.0, decision analytics	LUMS, Lahore
ID-11	Industrial system reliability, predictive maintenance	Beijing Institute of Technology, China
ID-12	Technology road mapping	UNIDO, Islamabad, Pakistan

Table A1. Cont.

Participant ID	Expertise	Current Affiliation
ID-13	Project planning, supply chain management	TEVTA, Pakistan
ID-14	Industrial waste management, production planning	Al-Aziz Packages, Faisalabad
ID-15	Supply chain management, production planning	Waves, Lahore
ID-16	Applied artificial intelligence in Industry 4.0, big data	KAIST, South Korea
ID-17	Industrial automation, artificial intelligence	UET Lahore, Pakistan
ID-18	Additive manufacturing	Hong Kong University, Hong Kong
ID-19	Project engineering, HSE, operations management	Shell, Islamabad, Pakistan
ID-20	Systems integration, flexible manufacturing	Tsinghua University, China
ID-21	Cloud computing	Saudi Aramco, Saudi Arabia
ID-22	Artificial intelligence, lean transformation	University of Punjab, Lahore
ID-23	Internet of things, big data	General Electric, Canada
ID-24	Cloud computing, augmented/virtual reality	University of Cambridge, UK
ID-25	Lean production system, agile and green manufacturing	Mahmood Group of Textile Industries, Pakistan
ID-26	Flexible manufacturing, engineering management	University of Strathclyde, UK
ID-27	Internet of things, autonomous robotics	Coca Cola International, Pakistan
ID-28	Engineering management, artificial intelligence	Boeing, Canada
ID-29	Autonomous robotics	Vivo, Pakistan
ID-30	Big data analytics, artificial intelligence	University of Cambridge, UK
ID-31	Engineering management, production planning and control	Honda Motor, Japan
ID-32	Artificial intelligence, production planning, engineering management	Style Textile, Pakistan
ID-33	Engineering management, digital planning	IGI Global, Pakistan
ID-34	Additive manufacturing, systems optimization	University of Leeds, UK
ID-35	Robotics and automation, Industry 4.0, digital manufacturing	Hong Kong University, Hong Kong

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