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Impact of I4.0 Technologies and their Interoperability on Performance: Future Pathways for Supply Chain Resilience Post-COVID-19

Abstract

Purpose – This study aims to investigate the impact of I4.0's technologies and their interoperability on Supply Chains (SCs) performance and how the integration of such technologies and their interoperability can create pathways for SCs resilience post-COVID-19. This is of paramount importance in the context of COVID-19 as the investigation around I4.0 technologies may provide relevant insights on how SCs may better respond to unexpected situations like the current pandemic with the use of digital technologies.

Design/methodology/approach– A survey research method was designed based on some constructs extracted from the literature regarding the main disruptive technologies, interoperability, elements of Supply Chains Processes (SCPs) performance such as integration, collaboration, transparency, efficiency, responsiveness, and profitability. The data were collected from March-July 2020 from different regions of the world when the peak of the first wave of the pandemic had occurred. The survey resulted in 115 valid responses. The study employed a combination of descriptive, correlation and multiple regression methods to analyse the data.

Findings– The study indicates that disruptive technologies significantly impact SCPs performance (integration, collaboration, responsiveness, and transparency) and their resilience. The findings did not support the notion that these technologies improve the efficiency of SCs, a significant contrast to the existing literature. Our findings also refute the existing understanding that interoperability moderates the impact of disruptive technologies on SCPs performance and enhancing the resilience of SCs. However, the findings show that the integration of I4.0 technologies and their interoperability has a positive impact on SCPs profitability.

Research limitations/implication – The findings strongly advocate that this integration plays an important role in improving SC performance, and a future pathway of supply chain resiliency post-COVID-19. Considering that the I4.0 trend will impact SCs in the coming years, this study brings a relevant contribution to researchers and practitioners.

Originality – This study makes a unique contribution by investigating a novel causal relationship between the main elements (I4.0 technologies, interoperability, processes performance, and strategic outcomes) related to the SC in this new context.

Keywords: Industry 4.0; Resilient Supply Chain; Process Performance; Strategic, COVID-19; Sustainability.

1. Introduction

Disruptions in global SCs are not uncommon and are witnessed at regular intervals due to natural disasters, conflicts, epidemics, or other events, occurring at different corners of the world. However, the ongoing pandemic has exposed the fragility of global SCs that have never been seen before (Ivanov, 2020; Javaid et al., 2020; Ghadge et al., 2020; Sharma et al., 2020; Kumar, 2020). This has attracted huge interest from academics, researchers and practitioners seeking to unravel the potential mitigation strategies to deal with SC disruptions. I4.0 was gaining momentum before the COVID-19 situation and its role may become even more critical in the backdrop of this ongoing crisis. Media outlets, news, blogs and recent research studies (Liu et al., 2020; Ivanov, 2020; Javaid et al., 2020) have all touted I4.0 technologies' relevance in addressing many of the challenges that COVID-19 has posed when managing SCs. For example, Queiroz et al. (2020) highlighted that I4.0 and digital manufacturing can play a critical role in SCs resilience and ripple effect control during this ongoing pandemic. Similarly, Javaid et al. (2020) reported that I4.0's remote operating capability using smart technologies has helped manufacturing companies during this COVID- 19 outbreak. I4.0 is significantly changing how SCs are managed to create and deliver value to customers (Porter and Heppelmann, 2014). According to Kagermann et al. (2013), I4.0 goes beyond organisations' boundaries and it needs to be part of a nation's strategic agenda as it will be a crucial factor of global competitiveness.

From the SC standpoint, studies on I4.0 are in the early stages. This demands new research to acquire further understanding related to the phenomenon of I4.0 technologies (Büyüközkan and Göçer, 2018) and its role in the context of the global scale disruptions such as the COVID-19. Frederico et al. (2019) point out the need for more empirical studies to investigate the relationship between disruptive technologies and SCs. Various researchers have reported that these revolutionary technologies will cause significant impacts on SCs in the coming years (Tjahjono et al., 2017; Stevens and Johnson, 2016). Recent studies in the context of COVID-19 have already shown that businesses engaged in digital manufacturing networks seem to be better positioned in crisis times (Kumar, 2020; Queiroz et al. 2020; Ivanov, 2020). Disruptive technologies, especially IoT and Cyber-Physical Systems (CPS), affect products and services, business models, markets, the economy, work environment, people and organisational skills, changing entirely SCs (Pereira and Romero, 2017; Lv et al., 2020 a,b). SCs can be ominously transformed, but at the same time, benefitted as these transforming technologies are implemented. Thus, it is essential to clearly understand the transformational process (Schrauf and Berttram, 2016). In this sense, the development of concepts and methods, beyond following only the technical side of I4.0 technologies become relevant (Wu et al., 2018). Concerning SCs, these disruptive technologies can directly influence the performance of processes and SC strategic outcomes (Duman and Akdemir, 2021). However, these technologies must be connected and communicate with each other. This is related to their Interoperability. Some researchers have considered Interoperability as an important element to allow a connection between all technologies involved in a SC (Büyüközkan and Göçer, 2018; Ghobakhloo, 2018; Hofmann and Rüch, 2017; Tjahjono et al., 2017; Wu et al., 2016; Tu, 2018; Goodarzian et al., 2021). Lu (2017) points out that interoperability is one of the key factors to be taken into account in the implementation of I4.0 with respect to SCP. It means that two or more systems can understand one another and share their functionalities (Chen et al., 2008).

Once these technologies are capable of connecting effectively, they will directly influence SCP. This will affect SC performance in terms of Integration (Kache and Seuring, 2017; Ghobakhloo, 2018; and Büyüközkan and Göçer, 2018, Ghadge et al. 2020; Awan et al., 2021a), Collaboration (e.g. Pfohl, Burak and Kurnaz, 2017; and Tu, 2018), Efficiency (e.g. Barreto, Amaral and Pereira, 2017; and Haddud et al., 2017), Transparency (e.g. Pfohl, Burak and Kurnaz, 2017; Hofmann and Rüch, 2017 and Kache and Seuring, 2017, Ghadge et al. 2020), and Responsiveness (Schauf and Berttram, 2016 and Büyüközkan and Göçer, 2018). This research focuses on these five elements, i.e., integration, collaboration, efficiency, transparency, and responsiveness. If these processes performance characteristics are positively influenced by disruptive technologies in terms of these five elements, it is likely to lead to profitability. Some studies have already considered the impact of disruptive technologies on the profitability of SCs (Tjahjono et al., 2017; Haddud et al., 2017; Kache and Seuring, 2017; Büyüközkan and Göçer, 2018).

This research brings a robust contribution to both the theory and practice of supply chain management (SCM). Its relevance is based on the aspects of novelty, research topic and research framework. From the novelty perspective, previous research studies are more related to some specific technologies and don't take into account the COVID-19 context. Furthermore, they do not approach the impacts of the main set of I4.0 technologies considering a comprehensive range of elements of SCP and linking them to strategic outcomes and interoperability. For instance, Haddud et al. (2017) investigated the impact of IoT on internal and external SC integration. Liu et al. (2016a) evaluate the linkage between information technology, integration, and performance (financial). Afshan et al. (2017) and Li et al. (2016) analyzed the impact of information technologies on SC collaboration and financial performance. On the other hand, Wadhwa et al. (2010) and Cho, Ryoo and Kim (2017) investigated the effects and relations between information systems, transparency and SC performance. In relation to responsiveness, Kim et al. (2013) and Cai et al. (2016) studied the impact of information technologies on SC responsiveness. Similarly, research exploring interoperability is very limited. For example, Chen, Doumeingts, and Vernadat (2008) approach architectures for enterprise integration and interoperability and Mouzakitis, Sourouni and Askounis (2009) communicated findings from the relation between enterprise interoperability and SC integration. Hence it is evident that a research gap exists in this domain and compels a study on the comprehensive impact of disruptive technologies on SCP's performance and profitability. Moreover, in times when SCs performance is being challenged amid sudden and impacting events like COVID-19, it becomes important to understand the relationship between I4.0 technologies and their interoperability with SC performance in the context of this historical event

Within the COVID-19 context, Van Hoek (2020) has pointed out the importance of rethinking SCs, suggesting more research regarding the impacts and new perspectives on how to manage SCs amid unexpected events. Some authors have also suggested the deployment of specific topics to take into consideration the sustainability aspect of SCs on the face of COVID-19 (Sharma et al., 2020) as well as the development of more resilient SCs (Rajesh, 2021, Novak et al., 2021). Furthermore, Queiroz et al. (2020) emphasized that under the pandemic outbreak there is a need for global SCs to be more integrated and digitally ready. This assertion was also supported by Ivanov (2020), who suggested that the digitalization of the SCs enhances the operational flexibility of SCs and hence improves the quality of the response to outbreak-related disruptions. Yet, Ivanov and Dolgui (2020) argue that I4.0 significantly improves the decision-making process through the enhancement of data analytics applications, effectively supporting SCs during severe disruptions. As studies relating to I4.0 under disruptive situations are in the early stages, the ongoing COVID-19 provides a unique opportunity to contribute to this research gap. This highlights the importance of the subject herein addressed in this paper.

Hence, considering the aspects discussed, research studies approaching the importance, impacts, barriers, and challenges with regards to I4.0 technologies become relevant in the current context as this can significantly contribute to the academic literature and the practice of SCM involving I4.0 initiatives. Amid the COVID-19 pandemic, the need for further understanding of I4.0 technologies impact becomes crucial. It is also important to deploy research studies not only on the technologies themselves but also considering managerial issues. As has been highlighted earlier, previous research studies are more focused on specific elements of SCP and its relationship with technologies. Also, they do not strictly approach the technologies of I4.0 but information technology in general. Furthermore, none of these studies considers the relationship between technologies, interoperability processes and strategic outcomes such as financial performance. Neither, there have been any empirical studies investigating these relationships in the COVID-19 context. This further highlights the novelty and originality of this study. Taking into consideration the purpose of this research and the arguments herein discussed, the following research question guides this study:

RQ: What is the impact of I4.0 technologies and their interoperability as a moderating factor on the performance of SCs and their resiliency amid the COVID-19 pandemic?

The results from the study can provide significant insights into future research deployment as well as assist practitioners involved in I4.0 initiatives. We, therefore, developed a conceptual framework demonstrating a clear cause-and-effect relationship between I4.0 technologies, interoperability, SCP and strategic outcomes to enhance the resilience of supply chains to deal with disruptions. The study adopts a quantitative survey research method to validate the hypotheses developed from an extensive literature review.

This paper is structured as follows: the next section presents the theoretical background, the conceptual framework and the formulation of hypotheses. The third section presents the collection of data and its analysis. The fourth section introduces and discusses the findings. The fifth section highlights the theoretical and practical contributions derived from the present research. Finally, Section 6 concludes this study by highlighting the limitations, theoretical and practical implications and future research directions.

2. Theoretical Background and Research Framework

This section discusses the theoretical background with regards to disruptive technologies, including interoperability, SCP's Performance elements and SC Profitability. A set of hypotheses are formulated based on the conceptual framework.

2.1 Disruptive Technologies

Disruptive technologies in SCs are those which come from I4.0. These technologies significantly impact SCP. As discussed previously, the main technologies of I4.0 include CPS, IoT, Big Data Analytics (BDA), Cloud Computing (CC) and Cyber Security Systems (CSS) (Awan et al., 2021b).

CPSs are systems, based on automation, which use integrative and new functionalities through networking, enabling the connection of physical reality operations with computing and communication infrastructures (Lu, 2017). Cyber-Physical Systems (CPS) provides a self-executed and controlled SCP enabled by a set of I4.0 technologies such as artificial intelligence, robotics, 3D-printing and augmented reality acting with IoT. Ivanov and Dolgui (2020) highlighted that CPSs have significantly transformed SCs by making them more resilient. This has helped businesses to manage the complexities arisen due to the COVID-19 outbreak. In relation to IoT, according to Büyüközkan and Göçer (2018), IoT is formed by objects that have an IP address for connecting to the internet, sending and receiving data, which generates an effective communication among these objects, network devices and systems. Yet, according to researchers, it is based on the use of unique identifiers for various types of assets among different industries on a global scale, seamless interoperability for exchanging sensor information in heterogeneous environments, the establishment of trust and ownership of data and overcoming privacy issues. Lu (2017) emphasizes the relevance of IoT and suggests that as a complex CPS, IoT is responsible for integrating several devices through sensing, identification, processing, communication, and networking capabilities. It is formed by machines and equipment, networks, the cloud, and terminals. Moreover, IoT systems can be integrated with self-optimization and autonomous decision-making mechanisms, machines and equipment in other to generate automated processes and improve performance. The ability of IoT to collect real-time data improves communication between suppliers and buyers and simplify redistribution activities (Galanakis, 2020), thus helping organisations to manage their supplier-buyer relationships during the COVID-19 pandemic.

With regards to BDA, Büyüközkan and Göçer (2018) state that it is linked to the description of a huge amount of structured, semi-structured or unstructured data that can be mined to generate relevant information for SCs. It is crucial to achieving transparency and productivity through the use of predictive informatics tools (Lu, 2017, Rajesh et al., 2021). Lu (2017) further points out that prognostics-monitoring systems are a trend of the smart manufacturing and industrial big data environment. Ivanov (2020) highlights that new digital technologies, including BDA, have the potential to improve the ripple effect control in cases of epidemic outbreaks. In this line, Javaid et al. (2020) further assert that big data can be highly useful for analysing and forecasting the reach and impact of COVID-19.

According to He and Xu (2015), CC brings a new networked manufacturing model to be applied in industry, guiding the future direction of manufacturing technologies. Tao et al. (2011) state that cloud manufacturing is the combination of some emerging advanced technologies (i.e., CC, IoT, virtualization, service-oriented technologies, and advanced computing technologies) with existing advanced manufacturing models and enterprise technologies. Futhermore, Büyüközkan and Göçer (2018) highlight that it provides a network formed by virtual services so that users can access them from anywhere in the world. In the wake of COVID-19, Lopes de Sousa Jabbour et al. (2020) suggested that digital technologies, such as CPS, IoT, collaboration portals and CC can enable visibility and velocity of SCs.

On Cyber-Security technology, Kache and Seuring (2018) consider it as one of the main challenges regarding BDA adoption in SCs. They also emphasize that data in SCs cannot be shared without the owner's consent and a balance amongst individual data privacy and SC needs must be reached. The recent COVID-19 break has shown that cyber-attacks have steadily become much more prevalent and hence it is vital for organisations to ensure information security along with their SCs (Lallie et al. 2020). Smith et al. (2007) also emphasize the importance of information security at SCs and proposed a security framework. According to these studies, information systems and technologies must consider factors such as information technology assets, threats, and vulnerabilities in considering the increase of SC integration and collaboration allowed by those technologies. Moreover, Williams, Lueg and LeMay (2008) affirm that SC security should be considered as part of a SC strategy. In this sense, Blockchain technology plays a central role in the improvement of cybersecurity in SCs (Kshetri, 2017).

2.1.1 Interoperability of Disruptive Technologies

Interoperability is a key element to ensure the effectiveness of disruptive technologies on SCP. The SC response to the COVID-19 pandemic, which can be potentially improved by disruptive technologies, depends on how interoperable those technologies are with one another. According to Ghobakhloo (2018), interoperability is the capability of systems to transact with other systems (i.e. human resources, smart products, smart factories and other technologies can communicate, connect and operate together at the same time). Lu (2017) states that interoperability is the ability of two systems to understand each other. It also refers to the capability of sharing information and knowledge. Lu (2017) further suggests that interoperability will synthesize software application solutions, business processes and the business context. Thus, interoperability has been considered as the key factor that allows the integration of various technologies as well as the integration of SCs. For the interoperability between I4.0 technologies specific principles are required in order to ensure accuracy and efficiency. Eight principles are necessary for I4.0 technologies to be interoperable, namely: accessibility, multilingualism, security, privacy, subsidiarity, the use of open standards, open-source software, and multilateral solutions (Lu, 2017).

Trappey et al. (2017) emphasize the importance of considering standards in an IoT implementation, being that a facilitating factor to seek higher interoperability that can support other I4.0 technologies. A crucial factor of interoperability is to guarantee a deep and clear prescription of the common suite with requisite capabilities that must be linked to all information systems that desire to interoperate at a determined level of sophistication (Chen, Doumeingts and Vernadat, 2008).

Interoperability allows SCs to collaborate efficiently while preserving their own identities and the manner on how to do business using mechanisms that act as facilitators (Pazos Corella, Chalmeta Rosaleñ, and Martínez Simarro, 2013). Interoperability can also be considered as the moderator element because dependent variables will be influenced according to the level of interoperability. Considering the role of interoperability and its relationship between disruptive technologies and SCP as well as the research question, the following hypothesis is proposed:

H1– *Interoperability positively moderates the impact of disruptive technologies on SCP's performance amid the COVID-19 pandemic*

2.2 Supply Chain Processes' Performance

As established in the Introduction section, authors have mostly considered five elements of SCPs performance that are impacted by Industry 4.0 technologies, namely: Integration, Collaboration, Efficiency, Transparency and Responsiveness. These performance attributes are supported in the literature by authors such as Tjahjono et al. (2017), Kache and Seuring (2018), Büyüközkan and Göçer (2018), Awan et al. (2018), Frederico et al. (2019), Awan et al. (2019), and Ghadge et al. (2020). This is important in the current context of COVID-19 as those attributes may improve SC response amid unexpected events. Based on the literature review, the next sub-sections present the relationship between these elements and disruptive technologies in order to propose hypotheses for the research framework. With the same purpose, the relationship between these elements and performance in terms of the profitability of SCs is brought up.

2.2.1 Integration in Supply Chains

SC integration is understood as a strategic collaboration between the members of a SC, considering the internal perspective that is related to member departments and the external perspective being the cross-functional processes between suppliers, focal company and customers (Stevens 1989, Zao et al., 2011). For Stevens and Johnson (2016), SC integration is the alignment, linkage and coordination of people, processes, information, knowledge and strategies across all members of a SC. This is essential to facilitate the effective and efficient flow of material, information and knowledge in order to meet customer requirements. Particularly, in the current context, SC integration becomes essential to manage the disruption caused by the COVID-19 event (Liu et al., 2016b).

Siau and Tian (2004) state that the goal of SC integration is to link up the marketing place, procurement, manufacturing and distribution network, being information systems essential to achieving this. According to these authors, technologies can be an obstacle in terms of appropriate software and hardware to generate an effective integration in SCs. Liu et al. (2016b) consider that SC integration is based on the following elements: synchronized planning, operational coordination and strategic partnership.

Concerning the impact of information technologies on SC integration, some authors have shown that there is a direct impact (e.g. Gunasekaran and Ngai, 2004). Yet, in relation to the impact of integration on SC profitability, some researchers have identified a positive impact (Liu et al., 2016b). Specifically, about the impact of I4.0 technologies, Haddud et al. (2017) have shown that IoT technology directly impacts internal and external SC integration. Nonetheless, IoT helps not only in SC integration itself but also in the integration of technology packages inserted into the SCs. In the same sense, Ghadge et al. (2020) suggest that disruptive technologies improve SC performance by providing a stronger connection between customers and channels, processes and devices and more integrated performance management. According to Ardito et al. (2019), technologies such as IoT, BDA, CC and CSS enhance the integration between SC and marketing. Hence, in the current COVID-19 pandemic situation, I4.0 technologies can play a crucial role in facilitating SC integration and influencing profitability.

Based on the aforementioned literature on integration and its relationship with disruptive technologies and their impacts on SC performance, the following hypotheses are proposed:

H2 – *Disruptive technologies positively impact SCP's integration amid the COVID-19 pandemic*

H3 – *SCP's integration enabled by disruptive technologies positively impacts SC profitability amid the COVID-19 pandemic*

2.2.2 Collaboration in Supply Chains

SC collaboration can be understood as a process of planning and executing processes as well as the combination and deployment of internal and external resources (Cai et al., 2016). SC collaboration is key in the current COVID-19 context, taking into consideration that it is related to how a SC is effectively managed. SC collaboration is linked to planning, forecasting, and replenishment (CPFR) into SCP (Li, 2012). For Cai et al. (2016), information technology is crucial for firms to use information as well as knowledge during collaboration within SCs. According to Afshan, Chatterjee and Chhetri (2017) collaboration in a SC is related to information and resources sharing. Jayaraman, Ross and Agarwal (2008) state that collaboration is a joint and coordinated effort between two or more entities in a SC seeking to reach a common target. For these authors, there are three types of collaboration across SCs: information sharing, interest alignment, and process standardization.

Cai et al. (2016) identified a strong impact of information technology on SC collaboration. Jayaraman, Ross and Agarwal (2008) also demonstrated that information technology such as web-based systems can effectively support collaboration in SC in terms of communication, information sharing, and processes execution. Li (2012) reported that the higher the level of technologies applied in SCs, the higher its performance is concerning the collaboration in its processes. It has been widely reported in the media recently that during the COVID-19 pandemic, SC collaboration is rapidly driving the recovery of many businesses. According to Afshan et al. (2017), SC collaboration through information sharing and quality enabled by information technology can positively impact SC performance in terms of profitability. More recently, Ghadge et al. (2020) showed that collaboration and data sharing support digital transformation in SCs, enhancing their performance. Specifically, for IoT, Cui et al. (2020) showed that the implementation of this disruptive technology may enhance collaboration in SCs. Blockchain technology can also enhance SC collaboration in SCs improving their resilience. This discussion leads to the formulation of the following hypotheses:

H4 – Disruptive technologies positively impact SCP's collaboration amid the COVID-19 pandemic

H5 – SCP's collaboration, enabled by disruptive technologies, positively impacts SC profitability amid the COVID-19 pandemic

2.2.3 Efficiency in Supply Chains

The ongoing pandemic outbreak has significantly affected the efficiency of operations and SCM business models (Queiroz, 2020). Efficiency in SCs can be improved by the use of technologies that allow getting more automated processes from the upstream to the downstream flow (Lee et al., 2011). In global SCs, according to Prasad and Sounderpandian (2003), information systems are crucial to achieving higher efficiency.

Jonsson and Gunnarsson (2005) emphasize that technologies based on the internet are a potential generator of efficiency for SCs. In the same sense, Kull et al. (2007) point out that web-based technologies can generate relevant improvements and make the SC more efficient. Also, these authors state that besides this fact, web-based technologies also help in better customer satisfaction. More recently, technologies such as IoT have successfully improved operating efficiency in SCs (Tu, 2018, Bienhaus and Haddud, 2018). For Bienhaus and Haddud (2018), higher SC efficiency is achieved through processes automation, processes and tasks simplification, inventory and labour cost reduction.

In this fourth industrial revolution, according to Tjahjono et al. (2017), efficiency is one of the main benefits obtained from the implementation of I4.0 technologies. For instance, Kache and Seuring (2018) explain that operational efficiency improvements can be achieved from Big Data implementation. This is because, with the use of BDA, productivity can be increased, and processes can become leaner through effective predictive analytics. Yet, with regards to BDA, Ghobakhloo (2018) suggests that this technology can provide improvements over the efficiency and performance of the asset of manufacturers. Hofmann and Rüch (2017) relate the importance of Cyber-Physical Systems to improve the efficiency of SCP.

Another way to achieve higher efficiency is through automation technologies. For Ghobakhloo (2018), automation also generates higher efficiency in terms of production processes. The next generation of SCs should be highly efficient based on fully automated processes and with the use of sensor technologies (Büyüközkan and Göçer, 2018). This will cause a straightforward impact on the profitability of SCs due to the significant cost reductions enabled by these technologies and their effect on SCP. Accordingly, considering efficiency, disruptive technologies and profitability relationships, the following hypotheses are proposed:

H6 – *Disruptive technologies positively impact SCP's efficiency amid the COVID-19 pandemic*

H7 – *SCP' efficiency enabled by disruptive technologies positively impacts SC profitability amid the COVID-19 pandemic*

2.2.4 Transparency in Supply Chains

SC transparency has received widespread attention over the years. However, in the wake of the ongoing pandemic there has been a demand for greater SC transparency. A sudden increase in demand due to panic buying and stockpiling efforts has amplified the bullwhip effect, which primarily happens due to the lack of transparency in the SC (Zhu, Chou and Tsai, 2020). According to Hofmann and Rüch (2017), transparency and visibility across the SC are some of the key characteristics of the Digital Era trend being incorporated into the own concept of I4.0. Barreto, Amaral and Pereira (2017) consider SC transparency and visibility as one of the main requirements to be met to achieve a SC 4.0 scope.

According to Zhu et al. (2004), information transparency is linked to the level of visibility and accessibility of information across the SC. Kache and Seuring (2017) state that SC visibility and transparency are related to real-time control and multi-tier (process, decision, and financial) visibility regardless of data location. Morgan, Richey Jr. and Ellinger (2018) affirm that transparency is associated with when members of the SC get full visibility and traceability of information from upstream to downstream operations processes. For Büyüközkan and Göçer (2018), the main benefit from disruptive technologies related to the transparency is the improvement generated on the capacity through a faster reaction against possible disruptions in the SC.

For Kache and Seuring (2017), SC transparency is one of the main opportunities to be impacted by the new disruptive technologies in the I4.0 era. They point out that SC transparency can leverage the efficiency and responsiveness in SCs. In the same line, Ghadge et al. (2020) found out that the rollout of I4.0 technologies increases the operational performance of SCs by improving SC transparency. Also, Ghobakhloo (2018) reports that I4.0 technologies can better support SCs in achieving complete information transparency. Dubey et al. (2020) propose that Blockchain technology improves SC transparency in humanitarian SCs seeking disasters relief. Yet in respect to humanitarian SCs, Rodríguez-Espíndola (2020) suggests that the disruptive technologies of I4.0 increase transparency across SC members in disruption situations.

Ghadge et al. (2020) found out that the rollout of I4.0's technologies increases the operational performance of SCs by improving SC transparency. Also, Ghobakhloo (2018) reports that I4.0 technologies can better support SCs in achieving complete information transparency. Zhu et al. (2018) have investigated the benefits of SC analytics technologies on SCs and the results have indicated that it can generate an unequal impact on SC transparency.

Wadhwa et al. (2010) analyzed the effects of transparency over SC performance. According to their findings, information transparency has a positive impact on SC performance. In a similar study, Cho et al. (2017) studied the relationship between transparency and SC performance. Not differently, their findings showed that overall transparency is positively associated with profit performance in SCs. More recently, Chod et al. (2020) showed that SCs can benefit from the implementation of Blockchain technology and increase profitability. According to Bienhaus and Haddud (2018), the adoption of IoT generates more visibility and transparency on information and material flows throughout the SC. Yet, considering IoT implementation, Tu (2018) also emphasize that this technology can radically support SCs concerning its transparency. With regards to BDA technologies, SC analytics can provide full transparency for SC members (Zhu et al., 2018). Therefore, taking into consideration these discussions, the following hypotheses are proposed:

H8 – *Disruptive technologies positively impact SCP's transparency amid the COVID-19 pandemic*

H9 – *SCP's transparency enabled by disruptive technologies positively impacts SC profitability amid the COVID-19 pandemic*

2.2.5 Responsiveness in Supply Chains

Responsiveness is related to how quick organisations can react against environmental changes (Bernardes and Hanna, 2009). Sharma, Adhikary, and Borahn (2020) highlight that in the event of any pandemic such as Covid-19, the responsiveness of SCP is critical. According to Kim, Suresh and Kocabasoglu-Hillmer (2013), technologies such as advanced manufacturing and e-platforms can increase SC responsiveness. Moreover, these authors have identified that the application of various technological elements at the same time can create synergic effects and significantly improve SC responsiveness. The same statement is given by Cai et al. (2016), who affirm that information technology capabilities are strong fosters to increase more responsiveness in SCs.

The implementation of advanced manufacturing technologies must be aligned with internal and external integration to leverage the level of responsiveness in the entire SC (Moyano-Fuentes, Sacristán-Díaz and Garrido-Vega, 2016). Sinkovics et al. (2011) refer to the importance of having information technologies fully integrated, as a relevant factor to make SCP more responsive. Abdoli, Bidhandi and Valmohammadi (2017) found out that responsiveness directly impacts the profitability improvement in SCs. This leads to our final set of hypotheses:

H10 – *Disruptive technologies positively impact SCP's responsiveness amid the COVID-19 pandemic*

H11 – *SCP's responsiveness, enabled by disruptive technologies, positively impact SC profitability amid the COVID-19 pandemic*

2.3 Supply Chain Profitability

Profitability is one of the most important strategic outcomes expected by a firm's shareholders. The impact of disruptive technologies over profitability can be significant because it supports the growth and financial sustainability of organizations. According to Shah and Shin (2007), the profit to sales ratio is the profit before tax in aggregation as a percentage of their sales being a frequently used indicator of whole profitability of a firm, industry and sector. Yet, a higher value of this ratio is linked to greater profitability. Mistry (2005) considers that profitability is associated with the margin profit, which is the benefit of the relation between cost reduction and sales increasing. The application of disruptive technologies may generate costs reduction improving the profitability by the improvement of process' performance elements such as integration, collaboration and efficiency, then increasing the profitability.

2.4 Conceptual Framework Development

Based on the theoretical discussions presented so far, a conceptual framework was developed (as presented in Figure 1) depicting the relationship between the disruptive technologies (independent variable), moderator (interoperability), elements of SC performance's (dependent variable), and profitability (dependent variable). Table 1 presents a synthesis of the literature used in the formulation of these hypotheses. This also presents the definition of variables that were the basis for the survey questions.

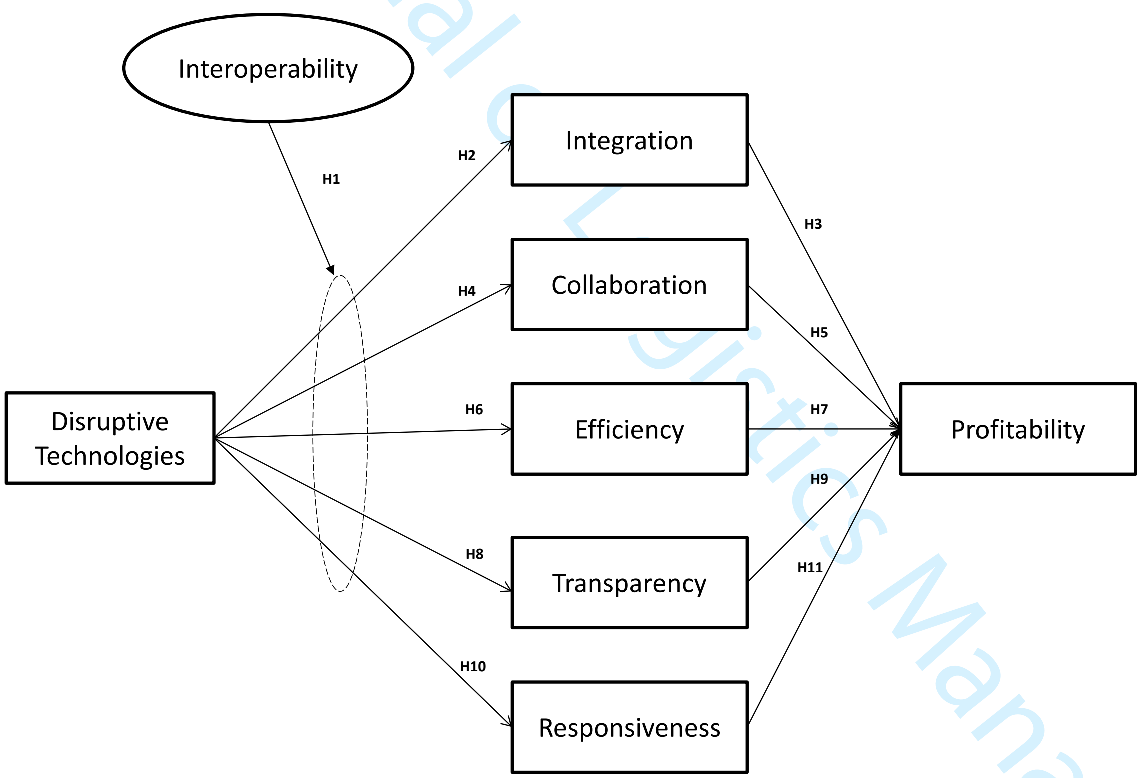

Figure 1: Conceptual Framework

Table 1. Synthesis of the theoretical background for hypotheses formulation and variables definition

INDEPENDENT VARIABLES	MODERATOR	DEPENDENT VARIABLES					
Disruptive Technologies	*Interoperability (H1)*	*Integration (H2,H3)*	*Collaboration (H4,H5)*	*Efficiency (H6,H7)*	*Transparency (H8,H9)*	*Responsiveness (H10,H11)*	*Profitability*
Ivanov and Dolgui (2020), Galanakis (2020), Javaid et al. (2020), Lopes de Sousa Jabbour et al. (2020), Büyüközkan and Göçer (2018), Kache and Seuring (2018), Kshetri (2017), Lu (2017), He and Xu (2015), Tao et al. (2011)	Ghobakhloo (2018), Lu (2017), Trappey et al. (2017), Chen, Doumeingts and Vernadat (2008), Pazos Corella, Chalmeta Rosaleñ, and Martínez Simarro (2013)	Ghadge et al. (2020),Ardito et al. (2019), Haddud et al. (2017), Liu et al. (2016), Stevens and Johnson (2016), Alfalla-Luque, Medina-Lopez and Dey (2013), Zao et al. (2011), Flynn, Huo and Zhao (2010), González-Benito(2007), Devarajaj, Krajewski and Wei (2007), Liau and Tian (2004), Gunasekaran and Ngai (2004), Stevens (1989)	Cui et al. (2020), Dubey et al. (2020), Ghadge et al. (2020), Afshan, Chatterjee and Chhetri (2017), Cai et al.(2016), Li (2012), Jayaraman, Ross and Agarwal (2008)	Queiroz (2020), Bienhaus and Haddud (2018), Tu (2018), Kache and Seuring (2018), Ghobakhloo (2018), Hofmann and Rüch (2017), Tjahjono et al. (2017), Lee, Palekar and Qualls (2011), Calantone (2007), Jonsson and Gunnarsson (2005), Prasad and Sounderpandian (2003)	Rodríguez-Espíndola (2020), Chod et al. (2020), Ghadge et al. (2020), Dubey et al. (2020), Zhu, Chou and Tsai (2020),Morgan, Richey Jr. and Ellinger (2018), Bienhaus and Haddud (2018), Büyüközkan and Göçer (2018), Tu (2018), Zhu et al. (2018), Hofmann and Rüch (2017), Cho, Ryoo and Kim (2017), Barreto, Amaral and Pereira (2017), Kache and Seuring (2017), Wadhwa et al. (2010), Zhu et al. (2004)	Sharma, Adhikary, and Borahn (2020), Abdoli Bidhandi, and Valmohammadi (2017), Moyano-Fuentes, Sacristán-Díaz and Garrido-Vega (2016),Kim, Suresh and Kocabasoglu-Hillmer (2013) Sinkovics et al. (2011) Bernardes and Hanna (2009)	Shah and Shin (2007), Mistry (2005)

3. Research Method

This section describes the research design procedure followed in this work. The steps involved in the research design have been recommended by various researchers (Hair et al., 2013; Field, 2017) and the same steps have been followed by various authors in the literature (Kumar et al., 2020). Figure 2 illustrates the research methodology framework of the study.

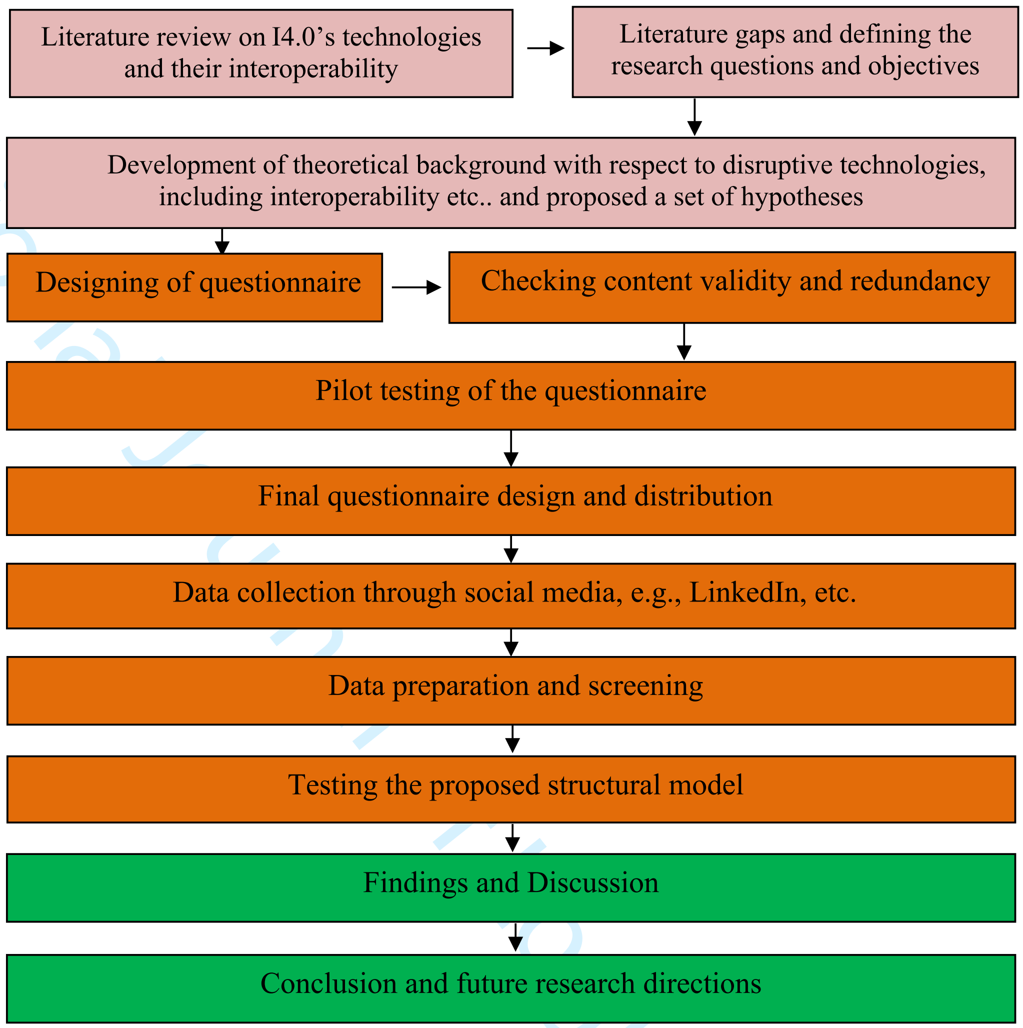

Figure 2. Research methodology framework of the study

3.1 Survey Approach

This study is explanatory in nature and hence a survey questionnaire-based approach suited best the data collection. A questionnaire survey-based study is a common approach to collect data in the operations and SCM fields (Flynn et al., 2018; Forza, 2002). According to Forza (2002), surveys can be divided into three typologies, namely: exploratory, confirmatory and descriptive. This research followed a confirmatory survey, which uses a theoretical framework as a basis to build well-established concepts (Forza, 2002).

3.1.1 Questionnaire Formulation

A set of constructs were developed based on the review of the literature as well as after having consulted a panel of five academic experts in the field of SCM and I4.0. These constructs formed the basis of the development of the survey questionnaire. The questionnaire developed is shown in Table 2. Ethical aspects were taken into consideration for which no identifiable information was collected. Similarly, respondents were asked to read and declare consent before starting the survey. In relation to the study demographics, questions were asked from respondents about their function in their organization, size of the company, annual turnover and location. The questions followed the rationale of the constructs and their variables (dependent and independent). Firstly, as per the SC experts' opinions, the widely used disruptive technologies (i.e., CPSs, IoT, CC, BDA and CSS) were considered in this study and their related questions were asked to the respondents. This was followed by questions related to the moderator factor (i.e., interoperability). Thereafter, the questions linked to SCP's Performance in terms of resilience (i.e., Integration, Collaboration, Efficiency, Transparency and Responsiveness) were asked. The final set of questions was related to Profitability. To investigate the COVID-19 context, a set of questions were also added to these constructs. All constructs were measured on a five-point Likert scale.

Table 2. Variable Deployment and Questionnaire Development

INDEPENDENT AND DEPENDENT VARIABLES AND MODERATOR DEPLOYMENT
Independent Variable
Disruptive Technologies in SC
1. Use of Internet of Things - IoT technology within SC
2. Use of Cloud Technology - CT platforms within SC
3. Existence of Cyber-Physical System - CPS within SC
4. Use of BDA tools within SC
5. Use Cyber Security - CS systems within SC
Moderator
Interoperability in SC: *How would consider the impact of following amid COVID-19?*
1. Connection Between Systems and Machines in SC
2. Understanding and Communication Between Systems and Machines in SC
3. Simultaneity in Systems and Machines Operation in SC
4. Integration between Systems and Machines in SC
5. Prescription of Capabilities for Common Suite in SC
6. Application of Interoperability Principles
Dependent Variables
Integration in SC: *Do technologies of I4.0 will improve following amid COVID-19?*
1. Internal Alignment and Coordination of SC Strategies
2. External Alignment and Coordination of SC Strategies
3. Alignment and Coordination of Internal and External SC Operational Issues
Collaboration in SC: *Do technologies of I4.0 will improve following amid COVID-19?*
1. Collaborative planning, forecasting and Replenishment (CPFR)
2. Internal and External Strategic and Operational Information Sharing in SC
3. Internal and External Resources Sharing in SC
4. Commitment and Trust amongst SC members
Efficiency in SC: *How would you consider the impact of I4.0's technologies on SC with regard to following amid COVID-19?*
1. Processes and Tasks Simplification in the SC
3. Cost and Inventory Reduction in the SC
3. Leaner Processes in SC
4. Productivity increasing in the SC
Transparency in SC: *How would you consider the impact of I4.0's technologies on SC with regard to following amid COVID-19?*

1. Internal and External Accessibility of Information within SC
2. Internal and External Visibility of information within SC
3. Real-Time Control of SC Processes
4. Traceability of Information from Downstream to Upstream SC
Responsiveness in SC: *Amid COVID-19 technologies of I4.0 has a positive impact on*
1. Readiness in Reacting Against Imminent Disruptions in SC
2. Readiness in Reacting Against Supply and Demand Change
3. Readiness to Attend Internal and External Requests of SC Members
Profitability in SC: *Do technologies of I4.0 can*
1. Increase Sales and Profitability
2. Reduce SCP Costs

3.1.2 Data Collection Strategy

This study followed a strategy and criteria to obtain responses from a specific population (i.e., practitioners and academics involved in the I4.0 phenomenon). The criterion was based on only considering experts having rich experience in I4.0 and SCM. These experts were identified and contacted through LinkedIn. LinkedIn is the most recognized website platform with professionals subscribers from different areas of industry and knowledge. In order to structure and automate the questionnaire and data analysis, the Qualtrics Software tool was used. The research team created a video in which the research team described the relevance of the topic, objective and how experts could participate. The video was posted two times on LinkedIn. Through this process and as per the set criteria, experts from the relevant field got a chance to participate in the survey. The demographics of respondents is illustrated in the Appendix I. Both LinkedIn posts and private direct messages were communicated in the period between March 2020-July 2020 (period of the pandemic when it was at its peak in most parts of the world, but particularly in developed countries). To measure Interoperability, it was important for respondents to have an understanding and experience of it. Therefore, the research team decided that the targeted respondents had to have expertise in Industry 4.0 technologies and their application in SCs. Thus, as per the data collection strategy, first, the profile of the expert was reviewed and then the respondent was selected to participate in the study. After following this rigorous process, a total of 350+ potential respondents were invited to complete the questionnaire. A total of 115 valid responses were obtained, resulting in a response rate of around 33 per cent. This response rate is well within the acceptable range as evidenced in previous studies such as Kumar et al. (2018).

3.1.3 Scale Development

To measure the constructs as shown in the conceptual framework, see Figure 1, a multiple items scale was developed, see Table 2. The first step before analysing the data was to test the reliability and validity of the data. To measure the reliability of the scales, a Cronbach alpha test was conducted. A value over 0.70 is generally considered to be acceptable (Vinodh and Joy, 2012). To test the convergent validity and discriminant validity, we computed the Average Variance Explained (AVE), Composite Reliability (CR), Maximum Shared Variance (MSV), and Average Shared Variance (ASV). For convergent validity, AVE should be > 0.5 and the Composite Reliability (CR) should be >.70. For discriminant validity, MSV should be < AVE and ASV < AVE (Dubey et al., 2021). The results of the reliability, convergent and discriminant validity are presented in Table 3. The results indicate that the Cronbach Alpha, AVE, MSV, CR, and ASV values for all the constructs were within the acceptable limits, thus confirming the reliability, discriminant and convergent validity of the constructs (Kumar et al. 2018). Since the CR and Cronbach Alpha values for transparency, responsiveness and profitability were high, the scores of the items were combined into a single construct. This approach was followed for all constructs for further analysis.

Table 3: Convergent Validity, Discriminant Validity and Reliability

Constructs	No. of Items	AVE (>.50)	CR (>.70)	MSV (<AVE)	ASV (<AVE)	Cronbach's Alpha (>.70)
Disruptive Tech	5	0.588	0.851	0.108	0.048	0.767
Interoperability	6	0.628	0.811	0.216	0.139	0.710
Integration	3	0.577	0.802	0.303	0.192	0.704
Collaboration	4	0.579	0.846	0.386	0.266	0.751
Efficiency	4	0.585	0.848	0.393	0.199	0.758
Transparency	4	0.998	0.999	0.280	0.155	0.999
Responsiveness	3	0.998	0.999	0.419	0.225	0.999
Profitability	2	0.907	0.967	0.419	0.254	0.826

AVE= Average Variance Explained; CR= Composite Reliability; MSV = Maximum Shared Variance; ASV= Average Shared Squared Variance

Table 4. Kaiser-Meyer-Olkin (KMO) Test and Bartlett's Test of Sphericity

Variables	KMO	Chi-Square	Df	Significance
Disruptive Tech	0.776	142.714	10	0.00
Interoperability	0.751	122.66	15	0.00
Integration	0.596	52.535	3	0.00
Collaboration	0.646	122.093	6	0.00
Efficiency	0.707	118.870	6	0.00
Transparency	0.855	1882.441	6	0.00
Responsiveness	0.791	1539.212	3	0.00
Profitability	0.601	83.373	1	0.00

The confirmatory factor analysis (CFA) conducted on the survey data indicated that all item factor loading values were > 0.6, which can be considered significant (Field, 2013; Kumar et al. 2018). The KMO value and Bartlett test for sphericity were used to indicate the extent of the integrated concept of the whole variables or scales. Table 4 presents the results of the KMO test. They suggest that the KMO values of all variables were > 0.6, except integration (0.596). However, it is still close to the acceptable value (i.e., 0.60). Bartlett's test of Sphericity for all variables was also significant ($p<0.01$). These results confirmed the validity of the constructs used in this research.

4. Research Findings and Discussions

As indicated earlier, the findings were obtained from 115 valid responses. The descriptive analysis of the data sheds some interesting insights. The demographics of the respondents is illustrated in the Appendix I. The survey was mostly responded to by managers/supervisors (i.e., operations, quality, production, process improvement, general, etc.) (42 per cent), this was followed by managing directors (19 per cent), engineers (i.e., operations, quality, production, process improvement, general, etc.) (8 per cent) and CEOs (8 per cent). Around 23 per cent of respondents did not specify their job positions. In terms of company size, 61 per cent were from large organisations (employing more than 2500+ employees), 24 per cent SMEs (employing less than 250 employees) and the rest of the respondents were from organisations employing between 251-2500 employees. In terms of the annual turnover of the organisations, coincidently around 30 per cent of respondents were from organisations with less than $100 million or more than $10 billion annual turnovers.

The first set of questions of the survey focused on understanding the disruptive technologies (CPS, IoT, CC, BDA and CSS). Around 90 per cent of respondents either agreed or strongly agreed on the potential of disruptive technologies in SCs. Only around 2 per cent of the respondents either 'disagreed' or 'strongly disagreed', whereas the rest of them (around 8 per cent) chose neither to agree or disagree. The belief in these technologies also shows a high level of awareness among the respondents. The second set of questions were focused on understanding the influence of interoperability on SC performance. As expected, the majority (93 per cent) of the respondents showed a high degree of confidence in the role of interoperability in SCs amid the COVID-19 pandemic.

The set of questions focused on SC performance measures (integration, collaboration, efficiency, transparency, and responsiveness) and its findings are shown in Figure 3. It is quite clear from Figure 3 that the respondents were mostly in agreement on the impact of I4.0 technologies on these variables during the pandemic. For example, respondents agreed/strongly agreed (91 per cent) that I4.0 technologies can help to improve the alignment and coordination of internal and external operational issues (integration) in SC amid the COVID-19 pandemic. Nearly 90 per cent of the respondents also agreed/strongly agreed that I4.0 technologies can help to improve commitment and trust (collaboration) amongst SC members during the COVID-19 emergency. Similarly, around 86 per cent of the respondents agreed/strongly agreed that I4.0 technologies help organisations to make their SCPs leaner (efficiency), whereas again around 86 per cent of the respondent agreed/strongly agreed that these technologies also improve internal and external visibility. Nearly 91 per cent of the respondents also agreed/strongly agreed that such technologies have a positive impact on SC readiness to reacting against imminent disruptions brought by the COVID-19 pandemic (responsiveness).

The final set of questions were based on the profitability dimensions, i.e., the impact of SCP on cost reduction and increase in sales (see Figure 4). Nearly 81 per cent of the respondents agreed/strongly agreed that I4.0 technologies would help in cost reduction. Around 74 per cent of the respondents also agreed/strongly agreed that I4.0 technologies are likely to boost sales and profitability amid COVID-19. During this pandemic, various scholars (Awan, 2019; Javaid et al., 2020; Ansar et al., 2020) and media outlets have already advocated the rollout of the I4.0 technologies to address many of the existing SC challenges of COVID-19. Our findings thus add to this debate by providing supporting empirical pieces of evidence.

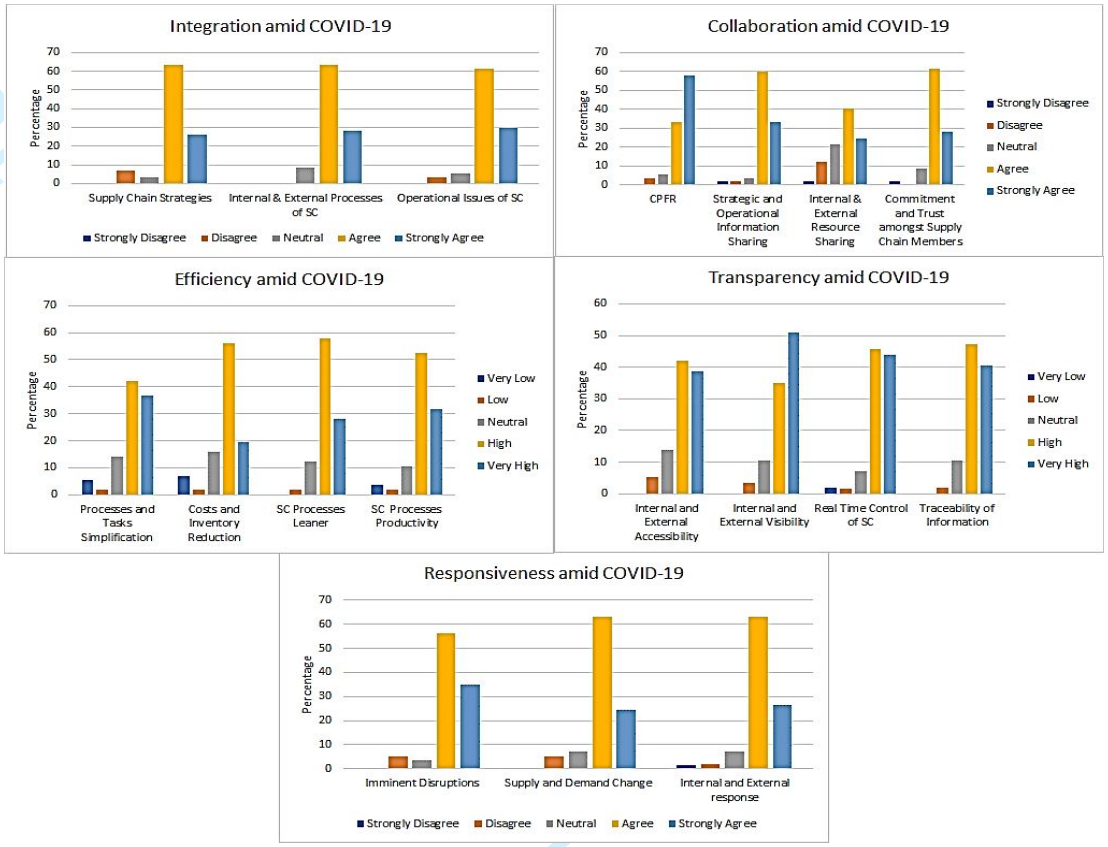

Figure 3: Impact of I4.0 technologies on Integration, Collaboration, Efficiency, Transparency and Responsiveness amid COVID-19

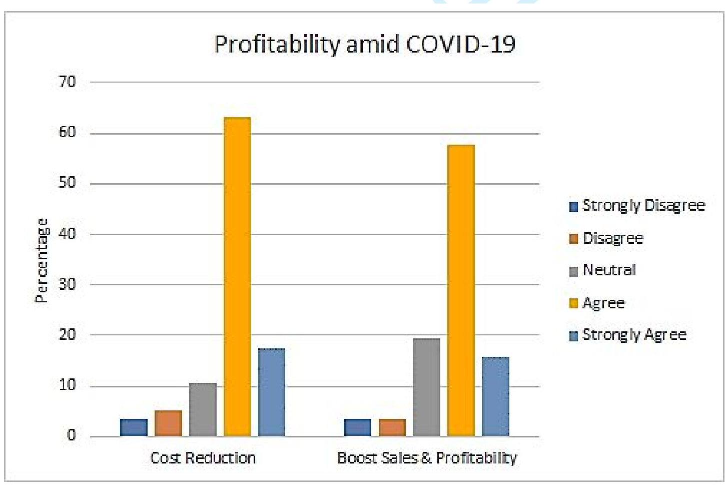

Figure 4: Impact of I4.0 technologies on a) Cost Reduction and b) Sales and Profitability

A correlation analysis between the variables was then conducted as shown in Table 5. The correlation analysis shows that most variables were correlated to each other, except for the correlation between disruptive technologies and efficiency. The first hypothesis H1 of this study focused on testing the moderating role of interoperability between the studied disruptive technologies and SCPs. Our assumption, based on the review of the literature, was that interoperability would positively moderate this impact. The correlation analysis showed that interoperability significantly correlates with all SCPs. To test the moderation effect of interoperability, we then followed Hayes' (2018) process macro and performed a moderated multiple regression for each SCP. However, the analysis showed that interoperability did not significantly moderate that relationship. Thus, our first hypothesis (H1) was not supported. The study conducted by Cabral and Grilo (2018) suggests that organisations, and their SCs, can develop different levels of interoperability and that only an 'appropriate' level of this characteristic will play a role in the performance of SCs. This may indicate why interoperability not necessarily moderates the impact of disruptive technologies on the performance of SCs and that companies need to achieve an 'appropriate' level for it to have a significant role in improving SC performance. Despite this, it is not clear what this 'appropriate' level should be if it exists at all, and how it could be measured and achieved. In addition, interoperability is a technical term and hence respondents may not necessarily have a good understanding of the term, which may have influenced our data. Thus, the results of our study have opened a research stream that would be worthy of exploring as part of the future research agenda on the subject.

Table 5: Correlations (Pearson Correlation)

Variables	Disruptive Tech	Interoperability	Integration	Collaboration	Efficiency	Transparency	Responsiveness	Profitability
Disruptive Tech	1							
Interoperability	.328**	1						
Integration	.213*	.450**	1					
Collaboration	.208*	.465**	.550**	1				
Efficiency	.079	.325**	.424**	.551**	1			
Transparency	.163*	.303**	.452**	.529**	.357**	1		
Responsiveness	.288**	.354**	.425**	.576**	.529**	.394**	1	
Profitability	.154*	.356**	.478**	.621**	.627**	.446**	.647**	1

** Correlation is significant at the 0.01 level (1-tailed)
* Correlation is significant at the 0.05 level (1-tailed)

The correlation analysis, however, indicates that disruptive technologies do positively impact SCP's integration (H2) as correlation was found to be significant (0.213*) at the .05 level. Similarly, correlations between disruptive technologies and the SCP's collaboration (H4) (.208*, significant at the .05 level), the SCP's transparency (H8) (0.163*, significant at the .05 level) and the SCP's responsiveness (H10) (.288**, significant at the .01 level) were found to be significantly and positively correlated.

Interestingly, our findings do not support the hypothesis (H6) that disruptive technologies positively impact SCP's efficiency, as correlation (.079) was found to be insignificant. To cross verify these findings, a regression analysis was performed, which also showed that the regression coefficient (β) was not significant. This is in sharp contrast to existing studies

(Barreto, Amaral and Pereira, 2017, and Bienhaus and Haddud, 2018) that have emphasized that SC efficiency greatly improves with the implementation of disruptive technologies. One reason that could be attributed to this finding is possibly the skills gap within SCs. The literature already indicates that the increasing technological complexity of frequently changing production, warehousing, distribution and logistics environments in I4.0 challenges workers to perform well (Telukdarie et al. 2018). The tasks they work on are getting less routine and ask for continuous knowledge and skills development. Madsen, Bilberg, and Hansen (2016) highlights that the most advanced skills will be necessary for companies to effectively manage the complex technologies in manufacturing facilities predicted for I4.0. This lack of skills in the I4.0 environment is potentially affecting the efficiency of the SCs.

The correlation analysis further indicates that SC integration and profitability (H3) are positively and significantly correlated (.478**, significant at .01 level). Similarly, correlation analysis supported H5 (.621**), H7 (.627**), H9 (.446**) and H11 (.647**), thus suggesting that SCP's performance is positively correlated with profitability. These results are in line with the existing literature that suggests the disruptive technologies positively affects the performance of SCP, which further positively affects the profitability (Afshan et al., 2017; Haddud et al. 2017; Büyüközkan and Göçer, 2018).

To further test the impact of SCP's performance on profitability, we conducted multiple regression analysis. Table 6 shows that SCP altogether explains around 56 per cent of the variance of profitability. The Durbin Watson test value (1.782) was also acceptable, as it was within the acceptable range of 1.50-2.50. These findings were further confirmed by the ANOVA analysis as it was found to be significant (Table 7). Thus, multiple regressions cross verified the findings of the correlation analysis and further confirmed hypotheses H3, H5, H7, H9 and H11 as the regression coefficients (β) were significant. Table 8 shows a summary of the hypotheses tested in this study. The next section concludes this study by highlighting the contributions, limitations and future research directions.

Table 6: Regression Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.762[a]	.580	.561	3.26133	1.782

a. Predictors: (Constant), Responsiveness, Transparency, Integration, Efficiency, Collaboration

b. Dependent Variable: Profitability

Table 7: ANOVA Analysis Summary

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1600.421	5	320.084	30.094	.000[b]
	Residual	1159.353	109	10.636		
	Total	2759.774	114			

a. Dependent Variable: Profitability

b. Predictors: (Constant), Responsiveness, Transparency, Integration, Efficiency, Collaboration

Table 8: Hypotheses Summary				
Hypothesis		**Result**	**Standardized Regression Weights**	**P-Value**
Interoperability (H1) (moderator)	→ SCP's Performance	Rejected	-	-
Disruptive Technology (H2)	→ Integration	Supported*	0.213	0.022
Disruptive Technology (H4)	→ Collaboration	Supported*	0.208	0.000
Disruptive Technology (H6)	→ Efficiency	Rejected	0.079	0.401
Disruptive Technology (H8)	→ Transparency	Supported*	0.163	0.000
Disruptive Technology (H10)	→ Responsiveness	Supported*	0.288	0.002
Integration (H3)	→ Profitability	Supported*	0.077	0.000
Collaboration (H5)	→ Profitability	Supported*	0. 193	0.036
Efficiency (H7)	→ Profitability	Supported**	0.291	0.000
Transparency (H9)	→ Profitability	Supported**	0.080	0.000
Responsiveness (H11)	→ Profitability	Supported**	0.371	0.000

*significance < 0.05 **significance < 0.01

5. Theoretical and Practical Contributions

This study has made both significant theoretical and practical contributions. Regarding the theoretical implications, the study makes a unique contribution by providing a comprehensive understanding of the relationship between I4.0 technologies, SCP's performance and strategic outcomes which have not been empirically tested in an integrated manner in previous studies. Additionally, testing their relationship in disruptive situations such as the COVID-19 pandemic further adds to the contributions of this research. This study confirms the majority of the relationships between the constructs as suggested in the literature (e.g., the impact of disruptive technologies on collaboration, integration, responsiveness, transparency and then on profitability). However, our findings also show that further research is required to explore the moderating role of Interoperability between I4.0 technologies and SCP's performance. Previous literature has indicated the importance of this relationship hence more evidence is needed to better clarify this unconfirmed relationship. Also, a deeper study of the impact of disruptive technologies on the efficiency of SCP is required as this was also not confirmed by our study and deserves further exploration in regards to why this is the case. Moreover, the understanding of other factors needed to implement the disruptive technologies that influence SCP's performance demands further investigation.

Practically, this research also brings timely and relevant contributions considering the current situation of the COVID-19 pandemic. It encourages further research and applications related to I4.0 technologies concerning the SCP improving their performance amid emergency and disruption situations. The results may incentivise SC practitioners and academics to rethink a transformation from traditional SCs to SCs 4.0 (i.e., SCs are driven by disruptive technologies) to improve SC responsiveness and profitability and minimizing the effects from unexpected events as faced during this ongoing COVID-19 pandemic. The findings show that respondents mostly agreed or strongly agreed that SCP's performance is impacted by disruptive technologies in order to allow SCs to provide a better reaction to the post-COVID-19 scenario. Similarly, a framework was also developed by Sharma et al. (2020) to enhance the survivability of a sustainable supply chain in COVID-19 and post COVID-19 scenarios.

Adoption of I4.0 technologies and their interoperability can substantially enhance the sustainable performance of SCs. It will provide flexibility in SCs to enhance their resilience capabilities to deal with ongoing and future pandemics (Belhadi et al., 2021). Additionally, the majority of the respondents considered that the interoperability of I4.0 technologies has a high or very high impact on the performance of SCP. Respondents also considered that efficiency and transparency are highly or very highly impacted by disruptive technologies amid the COVID-19 event. Concerning profitability, the responses were in favour of the positive impact on the SC profitability caused by SCPs supported by disruptive technologies during the coronavirus pandemic.

This research, and its results, thus bring relevant insights to SC practitioners who are involved in I4.0 initiatives, confirming the benefits that can be obtained by the implementation of disruptive technologies. Also, the research encourages organisations to consider I4.0 technologies as a strategic element, mainly concerning disruption situations such as the COVID-19 pandemic. The study herein suggests that disruptive technologies may lead to strategic benefits in terms of SC response as well as profitability improvement. Further, the study provides a discussion on how disruptive technologies will enhance firms' capability to handle post-COVID-19 scenarios and future pandemics.

6. Conclusions

The present study investigates the impact of I4.0 technologies on the SCP's performance and profitability, having interoperability as a moderator element in the context of COVID-19. A confirmatory factor analysis was performed on the proposed conceptual framework, see Figure 1, which consisted of 11 hypotheses that explored the relationship between the eight formulated constructs (i.e., Disruptive Technologies, Interoperability, Integration, Collaboration, Efficiency, Transparency, Responsiveness and Profitability). Reliability and validity tests were also conducted to ensure the robustness of the research, the proposed framework and its constructs. The findings presented in this study was based on 115 valid responses from various SC professionals and practitioners. The results indicate that interoperability does not significantly moderate the linkage between disruptive technologies and SCP's performance, despite the literature predicting this relationship. Thus, H1 was rejected. This possibly occurred due to the fact that interoperability is a difficult and not well-known concept, mainly regards its importance for the effectiveness of I4.0 technologies. On the other hand, the correlation analyses confirmed the hypotheses (i.e., H2, H4, H8 and H10) related to the influence of disruptive technologies on SCP performance. This empirical evidence shows how important the adoption of digital technologies might be to the SC response in events like COVID-19. This is due to the fact that performance attributes on the SCs process such as integration, collaboration, transparency and responsiveness allows SCs to be more proactive and quickly execute their typical process (e.g. purchase, manufacturing, transportation and distribution). Making an analogy from a practical standpoint, it is clear how many companies (e.g. companies based on e-commerce) which were better prepared in terms of technologies could rapidly respond to demand and supply variations during the pandemic. An exception occurs for H6, which is related to the influence of disruptive technologies on the efficiency of SCPs. This hypothesis was not confirmed, contrasting the literature. This may be explained due to efficiency depends on other factors besides only the adoption of disruptive technologies (e.g., skills required from SCs workers to operate these new technologies). With regards to the impacts of SCPs' performance on SC profitability, the results showed that integration, collaboration, efficiency, transparency and responsiveness have a positive impact, confirming hypotheses H3, H5, H7, H9 and H11. This was further verified by the regression model and ANOVA analyses, a summary is presented in Table 8. The adoption of I4.0 technologies will significantly enhance the resilient capabilities of supply chain management.

Various constraint factors that acted as research limitations were encountered. These are important to be considered in similar future studies. The first factor relates to the limited sample size of data collected, i.e., 115 valid responses, and the broad international scope of the study. Further, research should aim at increasing the sample size and conducting a regional study so particular factors such as culture, I4.0 maturity, local government policies, etc. can be taken into consideration and a generalisation can be achieved. A second limitation refers to the fact that the study was mainly focused on industrial experts for survey responses, whereas academic and research experts were excluded. Future research underpinning this work should not only deal with pragmatic sources but also involve expert academics. In this study, very few and widely used disruptive technologies were considered but in future research, other disruptive technologies like blockchain, AI and Robotics and 3DP can be considered. Finally, the Likert-style survey in the questionnaire instrument limits the ability of the industrial experts to express opinions other than the pre-set answers. To address this limitation, integrating this research approach with a qualitative interview-based approach would further enhance the contribution, generalizability and validity of the results.

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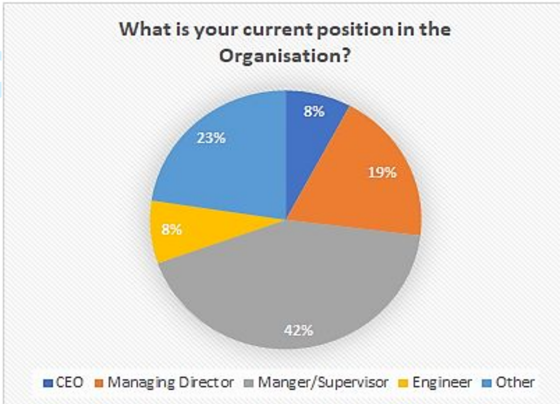
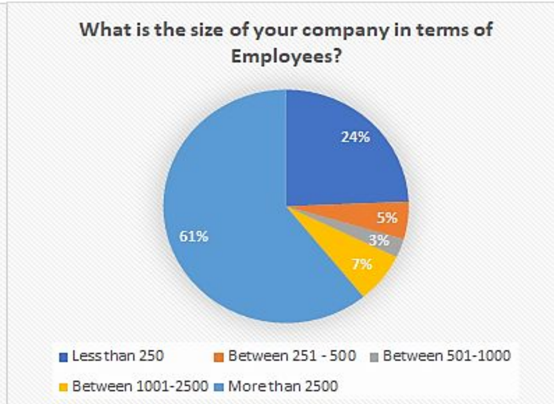
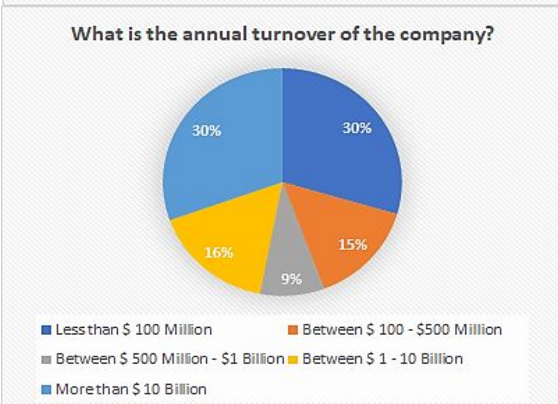
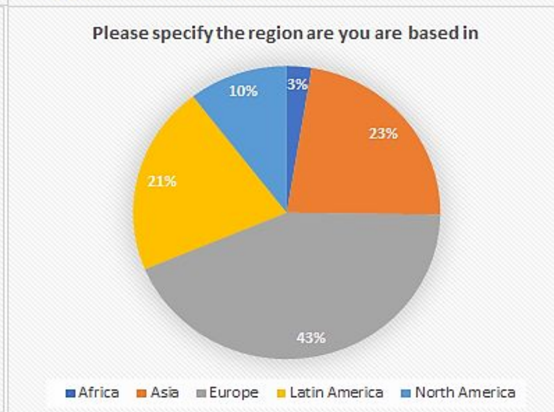
Appendix I


What is your current position in the Organisation?
8%
19%
42%
8%
23%
CEO
Managing Director
Manger/Supervisor
Engineer
Other


What is the size of your company in terms of Employees?
24%
5%
3%
7%
61%
Less than 250
Between 251 - 500
Between 501-1000
Between 1001-2500
More than 2500


What is the annual turnover of the company?
30%
15%
9%
16%
30%
Less than $ 100 Million
Between $ 100 - $500 Million
Between $ 500 Million - $1 Billion
Between $ 1 - 10 Billion
More than $ 10 Billion


Please specify the region are you are based in
3%
23%
43%
21%
10%
Africa
Asia
Europe
Latin America
North America