The Role of Industry 4.0 Technologies in Mitigating Supply Chain Disruption: Empirical Evidence From the Australian Food Processing Industry

Imran Ali, Ahmad Arslan, Zaheer Khan, and Shlomo Yedidia Tarba

***Abstract*—Supply chain disruption refers to a breakdown, often caused by an unforeseen incident or risk, in a supply chain's production or distribution process. Contemporary supply chains are globalized, complex, and extended, exhibiting an increased vulnerability to a multitude of risks and disruptions. However, the current trend of real-time data exchange through smart technologies, also known as industry 4.0, provides significant opportunities to reshape the conventional business operations and effectively cope with unanticipated supply chain breakdowns. Yet, limited attention has been paid to the role played by industry 4.0 technologies in mitigating supply chain risks and any resulting disruptions. By bringing together these inter-related yet often separate concepts, we devise a novel model that addresses this knowledge gap. In this article, we empirically test our model on a sample of 302 responses received from senior managers of the Australian food processing industry. We found that supply–demand mismatch, process risks, and transportation risks are currently the major sources of supply chain disruptions. Specifically, supply–demand mismatch appears to be the most severe and attention seeking risk, followed by process and transportation risks. We also reveal that industry 4.0 technologies significantly mitigate supply–demand mismatch and process risks and any resulting supply chain disruptions. Contrary to our expectations, however, the impact of industry 4.0 technologies on transportation risks is found to be positive but nonsignificant. This is the first empirical article to assess the extent to which the three critical supply chain risks may undermine firm performance and to explore the moderating effect of industry 4.0 technologies. We draw managers' attention to the detrimental impact of supply chain disruptions and the significance of industry 4.0 technologies in dealing with adversities.**

***Index Terms*—Digital technologies, external shocks, food industry, industry 4.0, supply chain (SC) disruption.**

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I. Introduction

Contemporary supply chains (SCs) are characterized by a high degree of dynamism and a multitude of risks, which may result in disruption through interalia, unanticipated process failure, supply-demand variations, and transportation breakdowns [1], [2]. An international survey conducted on 408 respondents from 64 countries revealed that 51.9% of businesses experience at least one risk-related SC failure [3]. The timely identification and mitigation of critical risks are, therefore, vital for the effective functioning of SCs.

As such, over the past two decades, the management of SC risks and disruption has emerged as a significant area of scholarly attention. However, despite several contributions (e.g., [1] and [4]–[8]), most studies are still based on the theoretical, conceptual, and assumption-based simulation/mathematical models [1], [6]. While such studies contribute to the extant literature in different ways, their findings often lack the support of real-world data, thus hampering the production of sound theoretical and managerial insights. Given this limitation, a few recent survey-based studies are evidenced; however, their focus remains on those risks that are specific to the traditional manufacturing industries, such as automotive, chemical, or construction (e.g., [7] and [9]. Given the dynamism of the business environment, risk profiles may vary over time and across different industry sectors, thus necessitating a separate study of the emerging threats and of any effective countermeasures to them. In this outlook, some studies have highlighted the criticality of supply–demand mismatch (SDM), process, and transportation risks (TRs) in causing SC disruption [1], [10]. Nevertheless, the extant literature lacks empirical insights into the extent to which these risks may disrupt firm performance (FP) in an SC.

Besides, in recent times, industry 4.0 technologies (I4Ts) have emerged as a new frontier in challenging and transforming the conventional business operations and helping cope with any unexpected disruptions. Although no universal classification exists, I4Ts include the Internet of Things (IoT), big data analytics, blockchain, cloud computing, robots, smart sensors, and three-dimensional printing. These technologies posses the incredible potential to revolutionize SC practices. For instance, the IoT supports real-time information sharing and visibility [11]; cloud computing generates a shared pool of big data, while blockchain enables traceability [12]; and automated robots reduce labor dependence [13]. Despite their widely conceptualized benefits, our knowledge of whether I4Ts might mitigate the impact of critical supply chain risks (SCRs) and SC disruptions remains underdeveloped. This article is, therefore, motivated by the need to understand the degree to which the three crucial SCRs mentioned above affect FP and the potential moderating influence of I4Ts, thus filling the knowledge gap found in the current literature. Specifically, we focused on the following three inter-related research questions.

1) To what extent do SDM risks cause SC disruption, and what effect do I4Ts have on this nexus?
2) To what extent do process risks (PRs) cause SC disruption, and what effect do I4Ts have on this nexus?
3) To what extent do TRs cause SC disruption, and what effect do I4Ts have on this nexus?

To address these research questions, our study built upon insights drawn from the resource-based view (RBV) [14], [15], which suggests that firms can develop a sustainable competitive advantage based on any unique resource and capabilities they possess. As 14Ts play a vital role in shaping the strategies enacted by firms in response to disruptions, these technologies can be viewed as important resources owned and leveraged by organizations to develop competitive advantages. To address the research questions, we utilized survey data drawn from 302 senior managers from the Australian food processing industry (FPI). With a market size of over US$100 billion, the worldwide FPI is a major contributor to the global economy, employment opportunities, and food supply [16]. Given the pressure for a sustained food supply, growing consumer concerns regarding food safety and quality (how food is produced and transported), and shorter product life cycles, there is a greater need for the FPI to innovate by taking the advantage of modern technologies; this, however, entails substantial investment, and the current lack of empirical evidence on their influence on the risk-performance nexus could, therefore, slow down or impede the adoption process. Hence, our study focused on the Australian food processing sector, which is among the nation's top three globally operating industries. Our study contributes to the existing body of knowledge on digital technologies and disruption management, which is currently lacking in empirical studies. Furthermore, while some studies have examined technological resources as predictors of performance (e.g., [17] and [18]), this research advances the empirical literature of RBV by recognizing I4T technological resources as significant moderators of the relationship between SCRs and FP.

The rest of this article is organized as follows. We present a synthesis of the literature on SCRs and I4Ts in Section II. Section III presents the study's hypotheses, empirical research design, and analysis. Section IV presents the research methodology. Then, the findings are discussed in Section V. Finally, Section VI concludes this article with the presentation of our study's key inferences and limitations, and of future research avenues.

II. Theoretical Background

This section presents our study's theoretical foundations and reviews the existing research on SCRs and I4Ts. This leads to identifying the potential gaps that formed the motivation for our study.

A. *Resource-Based View*

The RBV suggests that a firm's ability to acquire value-creating resources enables it to counter any threats and perform better than other firms in the same industry [14], [19]. While interfirm resource differences are widely accepted as an explanatory factor for superior performance; some resources may be imitated by competitors [14], [15]. The way a firm utilizes its resources and creates unique capabilities is what makes the real difference. Drawing upon the RBV, our study was motivated to identify the I4T resources acquired and exploited by firms to develop unique capabilities, which, in turn, enable them to mitigate SCRs and secure superior performance in the industry.

B. *SC Risk*

The concept of risk has long been discussed by scholars from diverse fields, such as economics, finance, and strategic management. However, most prior contributions, particularly in finance, have centered on classical decision theory, which assumes that risk is a variable that can have both positive and negative outcomes. Nonetheless, [20] revealed that most managers only consider the negative connotations of risk—loss or damage [20]. Correspondingly, many scholars in the SC management discipline have started to consider risk as a potential cause of loss, danger, or disruption. To this end, Peck [21] offered a structured definition and suggested that SCR is embodied by any incident capable of disrupting the flow of materials, products, or information from the original supplier to the end-consumer. Our study builds upon this definition of SCR [21].

Following such a negative notion of SCR, the literature has seen a proliferation of studies on the effect on the performance of various SCRs. Yet, most such studies are nonindustry specific and conceptual (e.g., [4], [6], and [8]), while others take qualitative approaches with limited generalizability (e.g., [1], [5], [10], and [22]). At the same time, some studies tend to take a mathematical/simulation model approach to SCR (e.g., [23]–[25]), while others, although of an empirical nature, focus on the traditional manufacturing industries (such as automotive, chemical, electronics, leather, and textile) with varied risk classifications and risk management measures [7], [9], [26].

Additionally, while the SC domino effect requires an understanding and management of any risks and disruptions at the SC level, numerous studies have taken a one-sided view, focusing only on any supply-side risks [1], [6]. From an SC perspective, Christopher and Peck [27] suggested three main risk categories: internal to the firm (e.g., process or control risks), internal to an SC (e.g., supply- and demand-related risks), and external to an SC or environmental risks (e.g., natural disasters) [27]. Consistent with this classification, some qualitative studies have recognized the following risks as unique to the food industry: PRs (internal to the firm), SDM and TRs (internal to the SC), and climate risks (external to the SC) [1], [10]. Being external to the SC, climate risks fall mostly outside of a firm's control. We, thus, focused on the first two categories of risk, which map the key components of the SC; that is, SDM (both supply and demand sides), PRs (focal firm), and TRs. These risks may cause SDM and, in turn, seriously disrupt the operations of the food industry [1], [10], [28]. However, given the vital role of the industry in global food security, the empirical evidence pertaining to such risks' specific influences on the organizational performance in the food industry needs to be examined.

C. Industry 4.0 Technologies

I4Ts—or the fourth industrial revolution—refer to 21st century fully automated and disruptive digital technologies. While there is no single classification, the most important elements of I4Ts are deemed to be the IoT, cloud computing, big data analytics, and robotics [29], [41]. The IoT is an interconnected network of devices (e.g., smartphones, smart sensors, and computers) that regularly exchange data, thus enhancing communication between all the objects in a system [30], [31]. Cloud computing enables the sharing of data in the main server to which all devices are connected. The joint application of the IoT and cloud computing enables dispersed devices to jointly generate big data [32]. The analysis of big data, also called the big data analytics, greatly supports decision making. Finally, programmed robots help to perform multiple operations that are either too complex or susceptible to risks of human error.

Despite the considerable proliferation of the literature, most studies are still built around conceptual debates, enumerating the potential benefits, the taxonomy, and the limitations of I4Ts (e.g., [11], [33], and [34]). Others have yielded descriptive statistics [35]–[38], [41] or assumption-based simulation/mathematical models [39], [40]. Although a few empirical studies have also been conducted, their focus differs from that of our study. For example, based on the data drawn from multiple manufacturing companies, Wamba *et al.* [41] explored the link between the big data analytics and FP. Tortorella and Fettermann [42] examined the link between lean production and I4Ts in Brazilian manufacturing companies. Finally, in a recent study, Kamble *et al*. [29] examined the impact of I4Ts on sustainability. Thus, despite its considerable contributions, most I4T pieces of literature have produced conceptual, descriptive, and simulation-based frameworks [29]. Empirical contributions are relatively scant or predominantly focused on the traditional manufacturing industries. To advance the knowledge of the characteristics and needs of specific industries, further studies should be conducted on the business impact of I4Ts in different industry settings [29]. As such, new empirical research investigating the impact of I4Ts on the SCR-performance nexus in the context of the FPI becomes indispensable to advance both theory and practice, as this industry plays an important role in enhancing global food security. To do so, we developed six testable hypotheses aimed at assessing the impact of the three critical SCRs mentioned above on FP in the FPI (a largely underexplored context) and the moderating role played by I4Ts.

III. Hypotheses Development

The RBV posits those resources that are valuable if they enable firms to acquire and exploit assets suited to develop the capabilities needed to counter threats, thereby exhibiting a superior performance [14]. Correspondingly, we formulated six hypotheses: first, to assess the impact of SCRs (threats) on FP (*H1–H3*) and, second, to examine whether and how I4Ts, as valuable resources, are helpful in countering the disruptions caused by risks and, thus, achieve better performance (*H4–H6*).

A. SDM Risks and FP

SDM refers to the differences between the expected and actual supply and demand scenarios [2]. Given the FPIs short shelf-life and seasonal production systems, the traditional make-to-stock and make-to-order measures do not apply to its products, leading to risks of over or undersupply. Furthermore, supply-demand alignment needs to be accurately forecast through precise and real-time SC information sharing and coordination [1]. However, many layers of intermediaries found in food SCs can hamper the real-time flow of information between the upstream suppliers and downstream buyers, resulting in product demand forecasting errors [43]. A higher than actual demand forecast can lead to oversupply and, thereby, to a decline in a firm's revenue. Conversely, a lower than actual demand forecast can result in the risk of supply disruption, tarnished customer satisfaction [2], and reduced market share. Given the above discourse, it may be argued that any SDMs may substantially disrupt FP in FPI SCs through reduced revenues, customer dissatisfaction, and market share losses. Thus, we suggested the following.

H1. SDM risks significantly undermine FP in the FPI.

B. PRs and FP

A process refers to a sequence of value-adding manual and mechanized activities that transform inputs (raw materials and/or information) into output (final products and/or services). PRs are mainly associated with disruptions affecting internal processes or with potential deviations from producing the desired quality and quantity at the right time [27]. Hopp and Spearman [44] posited two main types of variability in a process: *process variability*, which is mainly caused by a variety of incidents, such as machine downtime, setups, or operator unavailability; and *flow variability*, which is caused by manual operations and connectivity between stations. These factors may result in inconsistent throughput times, process yields, and product quality, which make the performance of the production process unpredictable and induce PRs. The disruptions caused by such risks undermine the capability of a manufacturer to fulfill customer orders and ultimately hinder efficient FP. As most food products (beverages, jams, juices, meat, and fish) have short shelf lives, they cannot be stocked for longer period of time. Thus, even a temporary disruption can make firms unable to buffer customer demand, tarnishing both customer trust and firm profitability. Prior research has also suggested that outdated processes and a lack of traceability may lead to risks of unacceptable food waste and, thus, to the losses linked to a firm's essential resources, such as energy, water, and labor [45]. Based on this discussion, we hypothesized the following.

H2. PRs significantly undermine FP in the FPI.

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C. TRs and FP

Given their perishable nature, fresh foods involve refrigerated transportation, which is inevitably susceptible to various SCRs [46], [47].

1) Over the past few years, cargo theft is on the rise with perishable food products being the goods most often stolen [48]. This is because these products can be easily and quickly consumed, leaving little or no footprints of the theft.
2) The second critical risk in food transportation is a lack of coordination and fragmentation resulting from the extension of today's SCs. If ambient container temperature conditions are not maintained through coordinated SC operations, there is no guarantee that the food will remain safe and fresh. This situation could cause customer dissatisfaction and declining market shares.
3) The third emerging risk associated with perishable product transportation is any unexpected delivery delay (e.g., due to lengthy border checks). In international transit, fresh foods travel long distances over many days, with transit time being a critical factor. Any delay in intended transit time caused by unforeseen incidents, such as bad weather or port congestion, can cause undesirable changes to the goods' organoleptic qualitative characteristics (flavor, odor, texture, and appearance).
4) While good quality packaging is indispensable to maintain the quality of perishable foods, packaging sourced from nonaccredited and/or cheap suppliers often fails to avoid deterioration due to extremely low temperatures with the high levels of humidity found within containers, thus resulting in food spoilage and returns.

Based on the above discussion, we hypothesized the following.

H3. TRs significantly undermine FP in the FPI.

D. I4Ts and SDM Risks

We argued that, based on the RBV, those firms that possess I4T resources will achieve better performance through reduced SDM effects. I4Ts enable the exchange of information and SC integration, thus synchronizing processes with suppliers to reduce delivery times and information distortions. For instance, IoT-connected radio-frequency identification (RFID) and electronic data interchange (EDI) technological resources enhance a firms' ability to share real-time information on the production, distribution, and sale of goods [49]. Those SC partners who instantly exchange information can work as a single entity. The effective use of relevant and timely information by all SC functional elements can help create resilience to divergent risks.

The constant exchange of information via cloud computing servers also generates a shared pool of big data, the analysis of which enables a firm to precisely forecast its inventory levels, reducing the impact of any supply-demand variance on the performance. As such, big data analytics, cloud computing, and the IoT can be seen as the key resources that create the capability to better forecast future customer demands and bring greater efficiencies in the distribution of products, thus controlling the supply-demand imbalance [29], [41]. Based on this discussion, we hypothesized the following.

H4. I4Ts negatively moderate the impact of SDM risk on FP in the FPI.

E. I4Ts and PRs

The ability to reconfigure organizational processes through the technological and administrative innovations is especially valuable in risky environments in which competitive advantages and positions diminish quickly because of changing technologies, customer needs, and market situations. However, the possession of I4T-related resources makes it possible to cultivate resilience and safeguard performance in many ways. For instance, in many labor-intensive industries, automated robots and drones can enable firms to build resilience against any risks linked to labor shortages, high labor costs, and input losses.

Besides, unforeseen machine breakdowns, which generate business cost through repair downtimes, are among the critical issues faced by today's heavily mechanized FPI. Given the short shelf lives, machine downtime can result in substantial food waste and loss of revenue. However, firms' leveraging of any IoT-connected smart sensors (resources) in their processes can reduce the effects of major breakdowns by generating quick alerts [33] that enable any hiccups to be fixed before major losses occur. Furthermore, the use of sensor-supported cameras (resources) can build resilience against accidents by scanning the environment for hidden objects, thereby reducing potential economic losses. Hence, from the RBV perspective, we contended that those firms that possess I4T resources will perform better by extenuating any PRs. Correspondingly, we hypothesized the following.

H5. I4Ts negatively moderate the impact of PRs on FP in the FPI.

F. I4Ts and TRs

Perishable food products require efficient transportation to ensure the delivery of the right quality and quantity of food to customers. With the conventional transportation methods, the timely and secure delivery of products becomes a challenging task. For instance, the traditional EDI documents typically go from the vendor to the customer, with no real-time information from the carrier beyond a carrier-generated tracking number; however, I4T resources—including an IoT-connected EDI, sensors, a geographical information system (GIS), and others—provide real-time information, thus alleviating transportation disruptions in many ways. First, an IoT-enabled EDI can update information in real time, giving firms greater visibility of when their goods will arrive. With the frequency of extreme weather patterns, the real-time updating of expected delivery information through IoT-connected RFID resources would be very beneficial in keeping transportation functioning more effectively [66]. Furthermore, in international transit, the use of smart sensors (resources) provides the capability of quickly adjusting internal temperature and humidity conditions in line with the exposure to several temperature regions on the way to the destination.

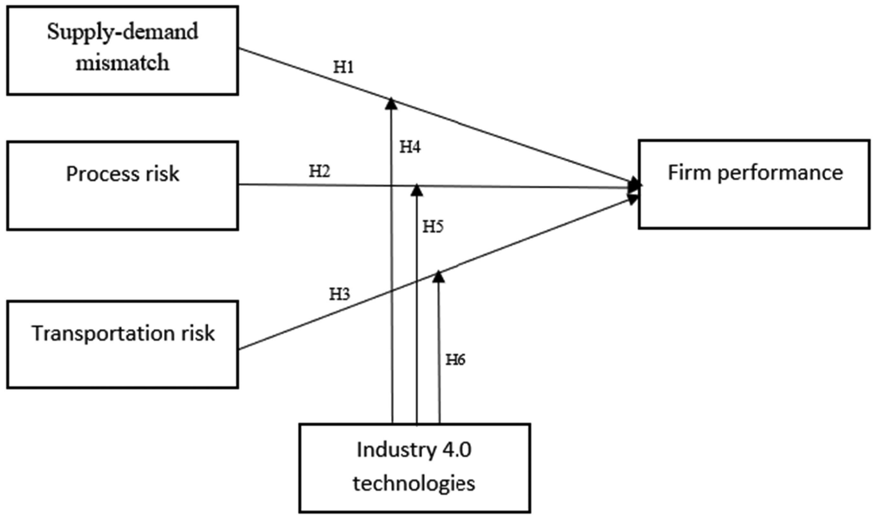

Fig. 1. Conceptual framework.

In addition, IoT-connected GIS and GPS devices (resources) help navigate and plan the itinerary of a shipment as it moves along sea, road, or rail routes to its destination [33]. A firm's possession of an IoT system with advanced asset tracking (resource) also provides an effective resilience to theft by providing locations and even live camera views suited to aid law enforcement in the event of a theft. Likewise, any sensors installed on the means of transportation provide useful data on whether a trailer's doors are open or closed or the cargo area is loaded or empty, providing the capability to reduce the threat of theft. Hence, based on the RBV, it can be argued that those firms that possess I4T resources will contain the impact of any TRs on performance and, thus, perform better than those firms that do not. The preceding discussion led to the following hypothesis.

H6. I4Ts negatively moderate the impact of TRs on FP in the FPI.

The review of the literature and the development of six testable hypotheses led to the conceptual framework, as shown in Fig. 1.

IV. Research Methodology

Consistent with the research questions, we employed a quantitative research method with an online survey as the primary data collection tool. The data were collected from senior managers of firms within the Australian FPI—one of the largest manufacturers and suppliers of premium quality foods across the globe [50], [67]—which transforms fresh agricultural products into a number of processed foods (cheese, bread, cakes, meat, biscuits, savory snacks, etc.) and beverages (wine, energy drinks, soft drinks, hot drinks, etc.). Over the past decade, the industry has faced a myriad of challenges, such as natural disasters, a pandemic, cost pressures, same day supply issues, and unpredictable customer patterns. However, little is known about the divergent sources of disruption and whether 21st century digital technologies have helped it achieve a sustained competitive advantage. Research on this large-scale, yet untapped, the industry is, therefore, needed to enhance its competitiveness, thus ensuring a sustained food supply for the ever-increasing global population.

To collect our data, we adopted a widely accepted procedure for sample selection and questionnaire design [51]. To ensure that all eligible participants would have an equal chance of being selected and that they would be representative of the whole population, we employed a random sampling method. Such a method, which reduces selection bias and increases the generalizability of results, also helps to identify and quantify any sampling errors. Before distributing the main survey questionnaire and in order to ensure its content validity and the reliability of the constructs, we ran a pilot with 54 participants. Then, we distributed about 1000 copies of the revised questionnaire and, having sent out two reminders to our potential respondents, we received a total of 302 usable responses. An analysis of our demographic data revealed that 30% of our participants were SC managers, 21% chief executive officers, 19% owner managers, 15% operations' managers, and 15% general managers. In regard to the professional experience, nearly 50% of our respondents had more than five years, 30% had more than seven, and the remaining 20% had ten years. These position and experience statistics indicated that relevant and expert practitioners had completed the survey. Furthermore, the analysis of firm size characteristics revealed that nearly 40% of our respondents were from small firms ($<$19 employees), while about 60% were from medium-sized ones (20–199 employees).

A. Constructs and Measures

The scales for "FP"—covering both market and financial performance—were adapted from the articles presented in [52]–[54]. Four measurement items for I4Ts (i.e., IoT, robot, cloud computing, and big data analytics) were drawn from past survey-based studies [29], [41], [42] and discussions held with industry practitioners.

We found no established scales for the constructs of PRs, SDM, and TRs in the context of this article. Therefore, following the approach of Wagner and Bode [26], we developed new items within a fully standardized questionnaire.

All items were measured on a five-point Likert scale. The measurement items for SCRs ranged from "not at all" (1) to "a very large extent" (5), while those for FP ranged from "significantly worse" (1) to "strongly improved" (5). Drawing upon prior research [41], [42], the items for I4Ts ranged from "not adopted" (1) to "successfully adopted" (5).

B. Data Analysis and Results

We completed the data analysis of our 302 responses in three steps: descriptive analysis, measurement model estimation, and structural model estimation.

The descriptive analysis entails the verification of sample adequacy, normality, multicollinearity, common method bias, and nonresponse bias. The Kaiser–Meyer–Olkin measure (0.814) and Bartlett's test for sphericity ($p<0.000$) confirmed our sampling adequacy for further analysis [55]. Moreover, the values of kurtosis (<1.13) and skewness (2.21) were found to fall within the acceptability range (<2 for kurtosis and <7 for skewness) [56], suggesting that our data were normally distributed. The variance inflation of factor value for the constructs was found to be much lower than the threshold value of 10 [57]; thus, multicollinearity was found to not be an issue in this research.

To avoid common method bias, we used several procedural measures. The results of Harman's single factor test indicated that the average variance attributable to a single factor was 35%, which was lower than the cutoff threshold of 50% [58]. In addition, we employed a marker variable technique [59] and found no correlation of marker variable with other variables. As such, we found that the common method bias was not a concern in our data.

Following the work of Mentzer and Flint [60], we checked for nonresponse bias by comparing the earliest 185 responses with the latest 117. The result of the independent sample *t-test* suggested a nonsignificant variance between the means of the two groups, indicating the absence of nonresponse bias.

C. Measurement Model Estimation

Before testing the structural model, a measurement should be affected to ensure the validity and reliability of the scales employed. The result suggested that the model fit indices were acceptable [61], [62], including $x2/df = 1.139$, $CFI = 0.911$, $GFI = 0.952$, $TLI = 0.893$, $AGFI = 0.931$, $IFI = 0.894$, $TLI = 0.901$, $RMSEA = 0.031$, $RMR = 0.028$, and $p = 0.000$, which ensured the unidimensionality of the scales [62]. Furthermore, we found the values of both Cronbach's alpha (α) and composite reliability to be much higher than the cutoff value of 0.70 (see Table I), indicating construct reliability, as suggested by Hair *et al.* [62].

The average variance extracted (AVE) values for each construct were found to be higher than the recommended value of 0.50 [63], thus supporting convergent validity. The items were loaded on their respective constructs (no cross loading was found) [62], thus confirming convergent validity. The square root of the AVE for each construct was found to be greater than the correlation between that particular construct and the others (see Table II) suggesting discriminant validity [63].

D. Structural Model Estimation

To test the hypothesized relationships, we used structural equation modeling through IBM SPSS Amos 26 in two steps. First, we assessed the direct effect of each risk on FP in the absence of I4Ts (see Fig. 2). The results revealed that the path coefficient from SDM to FP was negative ($\beta = -0.32$) and highly significant ($p = 0.0001$), thus supporting *H1*. Similarly, the path coefficient from PR to FP was found to be negative ($\beta = -0.26$) and significant ($p = 0.004$), providing support for H2. Furthermore, the path coefficient from TR to FP was found to be negative ($\beta = -0.19$) and significant ($p = 0.021$), supporting *H3*. Building upon the model fit indices of Hu and Bentler [61] and Hair *et al.* [62], our analysis indicated good model fit, including $CIMN/DF = 2.41$, $P<0.001$, $NFI = 0.954$, $CFI = 0.951$, $TLI = 0.945$, $RMSEA = 0.052$, *and* $SRMR = 0.043$.

In the second step, we evaluated the moderating effect of I4Ts on the risk-performance nexus. To this end, we created three interaction terms (moderating variables) in line with prior research [29], [46], including I4Ts∗SDM, I4Ts∗PR, and I4Ts∗TR. The model was run (see Fig. 2), and the results were recorded. The path coefficient for I4Ts as a moderator between SDM and FP was found to be positive ($\beta = 0.24$) and significant ($p = 0.003$), supporting H4. The path coefficient for I4Ts as a moderator between PR and FP was found to be positive ($\beta = 0.31$) and significant ($p = 0.0001$), supporting H5. The path coefficient for I4Ts as a moderator between TR and FP was found to be positive ($\beta = 0.11$) but nonsignificant ($p = 0.18$); thus, H6 was not supported.

E. Testing for the Control Variable

Given that the sample used for this article involved small, medium-sized, and large firms, firm size could potentially influence the key relationships in the proposed model—i.e., SCRs, FP, and I4Ts. The difference in the chi-square test indicated a nonsignificant p-value ($p = 0.188$); thus, firm size did not affect the main relationships in the proposed model.

V. Discussion and Implications

FPI firms operate in a fast-changing business environment and, therefore, require an effective and integrated supply chain risk management (SCRM) for their smooth operation. Addressing *H1–H3*, we found that SDM, PRs, and TRs may cause serious disruption in firm operational performance in the FPI. Our findings, thus, validate several early conceptualizations of the link between the three critical SCRs and FP [1], [6]. While all three examined risks were found to have a significant negative impact on FP, SDM was identified as the currently most daunting source of disruption. Presumably, this is due to the fact that the FPI industry operates in a highly dynamic business with an SC that involves multiple layers of intermediaries, causing information distortion between buyers and suppliers, and thereby imbalances between supply and demand. The risk of such SDM

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TABLE I
CONSTRUCT VALIDITY AND RELIABILITY

Constructs and items	Factor loading
Supply-demand mismatch (α = 0.94, CR = 0.90, AVE = 0.75)	
SDM1: Distorted information from business partners	0.88
SDM2: Imbalanced supply and demand	0.92
SDM3: Supply-demand forecasting error	0.96
SDM4: Price fluctuations	0.68
Process risks (α = 0.87, CR = 0.87, AVE = 0.71)	
PR1: Variance in daily output rate	0.93
PR2: Variance in product quality	0.87
PR3: Product waste or defects	0.69
PR4: Variation in order fulfilment	0.84
Transportation risks (α = 0.88, CR = 0.91, AVE = 0.77)	
TR1: Delivery delays	0.91
TR2: In-transit thefts	0.89
TR3: Packaging problems	0.85
TR4: Lack of transport coordination	0.86
Industry 4.0 Technologies (α = 0.89, CR = 0.88, AVE = 0.72)	
Internet of things	0.95
Cloud computing	0.68
Big data analytics	0.67
Robotics	0.79
Constructs and items	**Factor loading**
Firm performance (α = 0.82, CR = 0.92, AVE = 0.72)	
FP1: Return on investment	0.97
FP2: Market share	0.94
FP3: Profit margin on sale	0.81
FP4: The growth of sale	0.78
FP5: Customer satisfaction	0.74
FP6: Overall competitive position	0.82

is also exacerbated by seasonal production systems and volatile year-round customer demand patterns [1].

In terms of *H4–H6*, our findings revealed that I4Ts significantly reduce disruption by mitigating the negative impact of SDM and PRs on FP. Contrary to our expectations, however, the moderating influence of I4Ts on TRs was found to be positive but nonsignificant. There could be two possible reasons for this finding. First, transportation service is mostly provided by third parties, which may not be much aligned with the goals (digitalization initiatives) of key SC partners (suppliers, processors, and buyers). Second, in the FPI, there is no great tendency to use technologically integrated and fully automated transport services. Indeed, to reduce transportation costs, many primary producers in the food SC still use the traditional trucks or cheap

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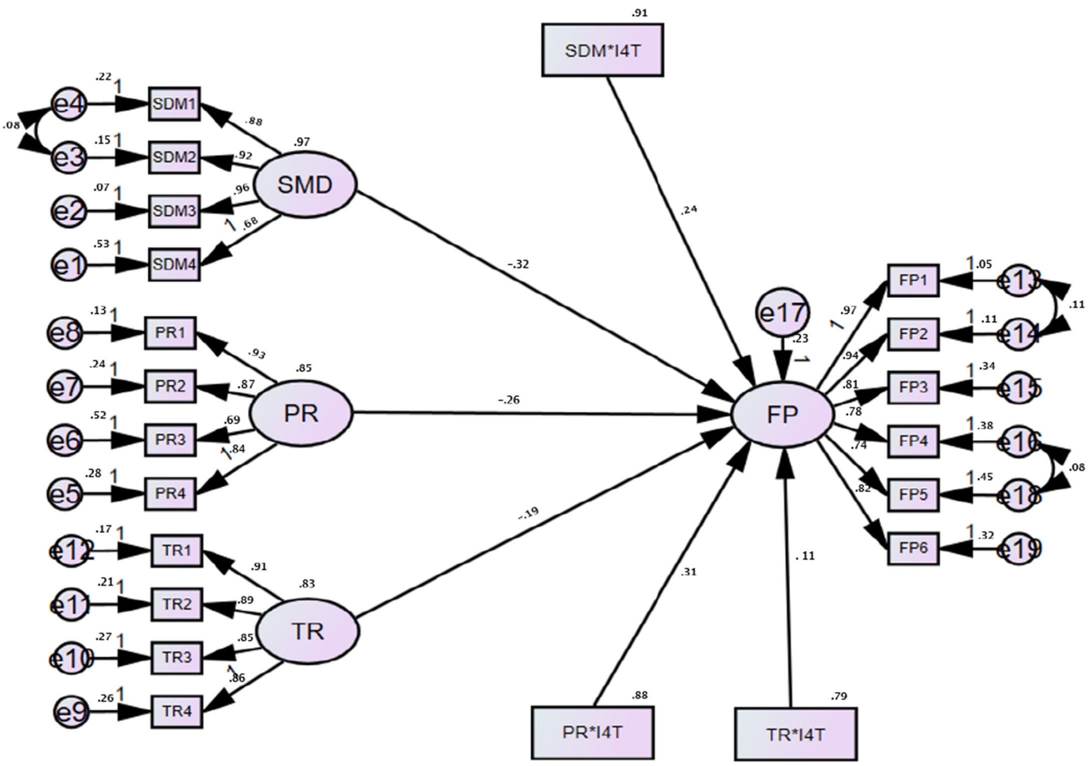

Fig. 2. Validated model demonstrating the role of industry 4.0 in SCR mitigation.

TABLE II
DISCRIMINANT VALIDITY

Construct	SDM	PR	TR	I4Ts	FP
SDM	0.91				
PR	0.56	0.89			
TR	0.77	0.67	0.81		
I4Ts	0.78	0.75	0.55	0.88	
FP	-0.51	-0.52	-0.76	0.72	0.83

transport services to deliver fresh food from farms to processors [46].

Nonetheless, our empirical findings expand the previous scholarship on the role played by I4Ts in many ways. Prior studies, for instance, have recognized that I4Ts have the potential to facilitate environmental control and protection, which may lead to sustainable performance [29]. We expanded upon prior scholarship and provided empirical evidence for the moderating influence of I4Ts on the relationship between SCRs and FP. In doing so, our study also responded to the call for more empirical research on the impact of I4Ts in various industry contexts [29].

Our findings also provide empirical support to those prior studies that established the links between the digital technologies and performance improvement through narrative literature reviews or qualitative approaches focused on the challenges to the adoption of I4Ts (e.g., [11], [37], [38], [41], and [64]).

A. Theoretical Implications

Our study makes four important contributions to the existing literature in the field.

1) Previous research had offered theoretical propositions on how I4Ts or SCRs influence a firm's (sustainable or operational) performance. However, empirical evidence on the interactive impact of SCRs and I4T on FP had been hitherto lacking. Ours is the first study to empirically investigate the relationship between SCRs, I4Ts, and FP, and to demonstrate that a firm's resources and capabilities play a vital role in enhancing its performance. We found that, while SCRs may cause serious disruptions, the presence of I4Ts reverses the disruptive and negative impact of critical risks, thus enabling firms to achieve a competitive advantage.
2) The extant research has yielded various theoretical assumptions on the extent to which SDM, TRs, and PRs may undermine FP in the FPI [1], [6]. Such assumptions could create confusion in the deployment of a firm's resources while dealing with such risks. Our study addresses this issue by quantitatively testing the extent to which each type of risk undermines FP and by identifying the risk type that requires the most attention (i.e., SDM). Our study also adds empirical insights to the recent research on SC disruption, which is driven by projection-based models [23], [65].
3) While some studies have examined technological resources as predictors of performance (e.g., [17] and [18]), our research advances the RBV empirical literature by

recognizing I4T resources as a significant moderator in the relationship between SCRs and FP. We argue that those firms that possess I4T technological resources and use them to gain disruption mitigation capabilities exhibit a nonsignificant impact of SCRs on performance, and thereby perform better than their counterparts that do not have access to or possess such resources.

4) Ours may be among the first studies to add the new construct of SDM along with validated measurement items. In today's complex and volatile business landscape, SDM is deemed to be a critical risk that needs to be assessed and managed [1], [2]. Our study, thus, provides a leeway for prospective research to accurately measure and manage SDM threats not only in the FPI but also in other industries—albeit with some contextual modifications in the measurement items.

B. Practical Implications

Our research presents significant implications for those policymakers and managers who aim to implement I4Ts to mitigate any disruptions caused by potential SCRs in FPI. We draw managers' attention to the potential disruption caused by three crucial SCRs (SDM, TRs, and PRs) and to the significant role played by I4Ts in safeguarding FP and achieving competitive advantage. While all three types of risk are critical, managers should focus on SDM, which has been identified the most daunting source of disruption. Disruptions related to SDM often manifest themselves through information distortion, forecasting errors, and fragmentation within various firm functions and among SC partners. An effective way to deal with such risks and the costly disruptions they may cause is to generate the internal and external information processing capabilities by using advanced digital technologies, such as the IoT, robotics, cloud computing, and big data analytics. These technologies can enable information sharing, visibility, cost optimization, and better connection and coordination [11]. For instance, IoT-integrated devices and sensors enable SC real-time information sharing, traceability, and visibility, thus monitoring any disruptions triggered by misalignment in supply and demand. Our analysis shows that the adopters of I4Ts suffer the least impact of SDM-related risks (information asymmetries, oversupply, undersupply, and forecasting errors) on performance. Furthermore, given the extended SCs and shorter product shelf lives associated with the FPI, TRs are becoming a critical challenge to business success. Our findings show the managers that investment in I4Ts may significantly reduce the disruption caused by TRs—such as delivery delays, packaging problems, thefts, and SC fragmentation—on performance. Besides, while PRs can seriously disrupt a firm's internal operations [1], our findings suggest that investment in I4Ts has excellent likelihood to combat PR-induced disruptions.

Finally, from a national policy perspective, our research is also expected to address the UN's sustainable development goals (SDGs) 2 and 9. Specifically, our study highlights the possibilities for small and medium-sized enterprises (SMEs) in the FPI to utilize I4Ts to reduce food losses and hunger (SDG 2) and to build resilient infrastructure and inclusive innovation (SDG 9). Our study shows the importance of I4Ts (innovation) in strengthening the FPI SC infrastructure through risk mitigation. Hence, our findings pave the way for policymakers to incorporate I4Ts in their policies as an essential element to ensure strong infrastructure and innovation.

VI. Conclusion

In this article, the purpose was to examine the extent to which various critical risks may cause disruptions, and how I4Ts can extenuate the impact of those risks and disruptions, thereby ensuring a sustained competitive advantage. Over the past decade, the literature had seen an exponential growth in studies on both SCRM and I4Ts; yet there was a lack of empirical research at the intersection of these two research streams. This means that most studies on SCRM and I4Ts were still conceptual, normative, simulation based, or qualitative in nature. This article, thus, filled the current knowledge gap by empirically investigating the effect of three critical SCRs on FP and the moderating impact of I4Ts. Our research determined that all three SCRs had a significant negative impact on performance; however, SDM was currently the risk most worthy of attention. We also found that I4Ts can significantly mitigate SC disruption by mitigating the negative impact of SDM and PRs on FP, thus ensuring a competitive advantage. Counterintuitively, however, our study failed to confirm the significant moderating influence of I4Ts on the relationship between TRs and FP.

A. Limitations and Avenues for Further Research

While our study made significant contributions, it does have some limitations that provide opportunities for further research. Our study was an early initiative that tests only the three most critical SCRs; future research could, thus, also examine other SCR categories (e.g., catastrophes, disasters, terrorist attacks, regulatory risks, etc.) and their interaction with I4Ts. Our study found a nonsignificant moderating effect of I4Ts on the nexus between TRs and FP, thus providing an opportunity to cross check this relationship through further research. Given the current dynamic and turbulent business landscape, modern SC was susceptible to disruptions [66], and future research could, thus, examine the influence of digital technologies on building SC resilience. Future research could also triangulate our findings by taking a qualitative approach. In our study, we adopted a cross-sectional analysis and a single respondent approach. Future research could involve longitudinal studies aimed at observing changes over time. As our study was conducted in a particular country (Australia) and on a specific industry's SC, it may be affected by geographical and sampling limitations. Our framework could, thus, also be expanded to some adjacent areas of research, such as green product innovation [67], [68] and sustainability [69].

In terms of the generalizability of our findings, the FPI is important in many countries across the world—such as the USA, China, the U.K., India, Italy, and Spain, among others—as such, our model and findings could be replicated across the globe. Given the nascence of the concept, there is a need for more empirical research on the role played by I4Ts in different contexts and industry settings. The SC structure and surrounding business environment in which a firm operates vary widely across various industry settings and countries; therefore, conducting further research focused on unique industry or country contexts is essential in order to gain multiple perspectives on the same phenomena/issues, thereby expanding our existing knowledge base. We also highlight the need for more research on SC 4.0, which refers to the implementation of I4Ts across SCs [70]. Another potentially fruitful area of research would involve testing the intervening impact of I4Ts at the intersection of SC disruption and knowledge management, which is an emerging concept [71]–[73]. Finally, the implementation of I4Ts can be a very costly process for small resource-constrained firms; it would, therefore, be interesting to examine how different types of firms manage the related costs and reap the optimal benefits of such emerging technologies.

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