UNIVERSIDADE FEDERAL DE SÃO CARLOS
CENTRO DE CIÊNCIAS EXATAS E DE TECNOLOGIA
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO

DÉBORA BIANCO

OPERATIONS MANAGEMENT IN TIMES OF COVID-19 CRISIS: THE ROLE OF MANAGEMENT APPROACHES TO ACHIEVE RESILIENCE.

São Carlos
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Tese apresentada ao Programa de Pós-Graduação em Engenharia de Produção da Universidade Federal de São Carlos, como parte dos requisitos para obtenção do título de Doutor em Engenharia de Produção.

Orientação: Prof. Dr. Moacir Godinho Filho

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RESUMO

A pandemia do COVID-19 teve consequências devastadoras em todo o mundo. Para limitar sua disseminação, diversas abordagens baseadas no distanciamento social foram adotadas por governos e indústrias, o que afetou as empresas e as cadeias de suprimentos. O surto de COVID-19 acarretou restrições sociais, tecnológicas e gerenciais para empresas de manufatura devido a recursos escassos ou interrupções na cadeia de suprimentos. Esta tese tem como objetivo investigar o papel do LM (Lean Manufacturing) e da Indústria 4.0 durante grandes rupturas e apresentar o legado da COVID-19 para gestão de operações. Para atingir este objetivo, foi realizado um survey, uma revisão sistemática da literatura (SLR) e entrevistas estruturadas com profissionas da indústria aeronautica. Na pesquisa empírica, investigou-se o papel do Lean Manufacturing (LM) e da Indústria 4.0 para melhorar a resposta e resiliência da empresa em tempos de crise sem precedentes. Foi utilizado modelagem de equações estruturais com estimativa de mínimos quadrados parciais (PLS-SEM) para analisar os dados coletados. Os resultados mostram que a forma com que as organizações responderam à crise da COVID-19 pode diminuir a perda de desempenho; o desempenho operacional pode ser aprimorado com o desenvolvimento de recursos inteligentes da Indústria 4.0 e práticas do LM. Demonstrou-se que as iniciativas da Indústria 4.0 apoiam a flexibilidade, agilidade e capacidade de resposta das empresas de manufatura no contexto da COVID-19. Além disso, discutiu-se os temas emergentes durante a pandemia ao apresentar uma agenda para pesquisas futuras. Este estudo pode ajudar os gerentes a alcançar estabilidade de desempenho durante tempos turbulentos, como a crise da COVID-19, adotando a Indústria 4.0 ou LM para tornar suas empresas responsivas e resilientes.

Palavras-chave: Lean Manufacturing. Indústria 4.0. Resiliência na cadeia de suprimentos. Legado da COVID-19.

ABSTRACT

The 2019 coronavirus pandemic (COVID-19) has had devastating consequences worldwide. To limit its spread, several approaches based on social distancing were adopted by governments and industries, which affected companies and their supply chains. The COVID-19 outbreak has entailed human, technological, and managerial constraints for manufacturing companies due to scarce resources or supply chain disruptions. This thesis aims to investigate the role of LM and Industry 4.0 during major breakdowns and present the legacy of COVID-19 on operations management. To achieve this goal a survey, systematic literature review (SLR), and semi-structured interviews with industry practitioners was carried out. In empirical research, we investigate the role of lean manufacturing (LM) and Industry 4.0 to improve the company's response and resilience in times of unprecedented crisis. We use structural equation modeling with partial least squares estimation (PLS-SEM) to analyze the data collected. Our findings show that companies' operational responses to COVID-19 can enable manufacturers to mitigate the loss of performance; operational performance can be enhanced by developing Industry 4.0 smart capabilities and LM practices. We demonstrate that Industry 4.0 initiatives support manufacturing companies' flexibility, agility, and responsiveness in COVID-19 context. Besides, we discuss the emerging themes during the pandemic while presenting a proposition for future research. This study can help managers achieve performance stability during disruptive times, such as the COVID-19 crisis, using Industry 4.0 or LM to make their companies responsive and resilient.

Keywords: *Lean Manufacturing. Industry 4.0. supply chain resilience. COVID-19 legacy.*

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LIST OF ACRONYMS

COVID- 19	Coronavirus Disease
HRD	Human Resource Development
JIT	Just In Time
LM	Lean Manufacturing
OSCM	Operation and Supply Shain Management
SARS	Severe Acute Respiratory Syndrome.
SC	Supply Chain
SCRE	Supply Chain Resilience
SCM	Supply Chain Management
SMEs	Small and Medium-sized Enterprises
SLR	Systematic Literature Review
TPS	Toyota Production System
TPM	Total Productive Maintenance
UFSCar	Universidade Federal de São Carlos
WHO	World Health Organisation

SUMMARY

CHAPTER 1 INTRODUCTION

This chapter explains what will be discussed throughout the thesis, there are the research presentation, the research relevance, the objectives, the methodological release, and the research structure.

1.1 RESEARCH PRESENTATION

The November 2023 World Health Organisation (WHO) situational report highlights the stark reality of a total of 772.052.752 confirmed cases and 6.985.278 deaths globally from COVID-19 (WHO, 2023). The novel coronavirus (SARS-CoV-2) outbreak and the related coronavirus disease (COVID- 19) started in China with more than 80000 confirmed cases. It was declared a global emergency by the World Health Organization (WHO) on 11 March 2020 (AKPAN; UDOH; ADEBISI, 2020). The COVID-19 outbreak is featured as a Transboundary Crisis that exceeds geographical, policy, cultural, public-private, and legal boundaries that normally enable the governor to classify, contain and manage a crisis. It mutates constantly, creating confusion about causes and possible consequences. It causes a disruption in the global economy spreading the effects throughout the supply chain (BOIN, 2019). There are several safe and effective vaccines that prevent people from getting seriously ill or dying from COVID-19 and are already being given to the population around the world. As of November 2023, 13.595.583.125 vaccine doses have been administered globally (WHO, 2023). Even though the population is already being vaccinated against COVID-19, the magnitude of the pandemic effects on the operation and supply chain management (OSCM) is still affect the organizations as well as the future of operations management.

COVID-19 disease is part of a large family of respiratory tract diseases that includes the common cold and its closest predecessor SARS (Severe Acute Respiratory Syndrome). Usually, COVID-19 symptoms are mild, but for some, especially those with pre-existing health conditions, they can be fatal (BRYCE et al., 2020; WHO, 2023; BOIN, 2019). The virus is spread through an infected person's cough, sneezes, or saliva droplets. Aiming at "flattening the contagion curve", quarantine and social distancing were imposed on organizations and society (SARKIS et al., 2020). The requirement for social distancing has strongly affected the routine of organizations and consequently the supply chains (SC). Most companies faced big challenges at every section of their SCs. Suppliers could not meet their delivery obligations, stricter hygiene standards up to complete plant closures affected organizations, and customer demand was highly unexpected (SPIESKE; BIRKEL, 2021; IVANOV, 2020a). The COVID-19 outbreak highlighted the vulnerability of SC. This scenario made evident the importance of building a resilient and responsive SC. Management approaches like LM and Industry 4.0 have played an important role in helping companies face the COVID-19 crisis and improve resilience.

Lean Manufacturing (LM) is a management approach whose principle is the development of people. Similar to other approaches, it also values the achievement of quality, cost, delivery, safety, and productivity objectives. The difference is that in Lean, employees are constantly trained to achieve these goals through skills development and team engagement (LIKER; BALLÉ, 2013). There are a lot of Lean practices addressed in the literature. According to Shah and Ward (2007), the most relevant are: JIT/continuous flow production; continuous improvement programs; lot size reductions; pull system/kanban; quick changeover techniques; self-directed work teams; total quality management; quality management programs; preventive maintenance; maintenance optimization; focused factory production; cycle time reductions; cross-functional workforce; safety improvement programs; process capability measurements; competitive benchmarking; new process equipment/technologies; planning and scheduling strategies. LM has been a well-recognized strategy for organizations even if applied in different countries, sectors, and Industry provides financial, operational, and environmental improvements (e.g., ZANON et al., 2020; NEGRÃO et al., 2020a; NOVAIS et al., 2020).

According to Schwab (2018), Industry 4.0 is a way of describing a set of ongoing and impending transformations in the systems that surround us. Industry 4.0 is a new chapter in human development on par with the first, second, and third industrial revolutions, and is again driven by the increasing availability and interaction of a set of unique technologies. This thesis assumes that smart manufacturing has developed in line with the recent evolution of the Industry 4.0 concept, the roots of which were initially in advanced manufacturing systems and their connections with other business dimensions of the company (FRANK et al., 2019; DALENOGARE et al., 2018). Smart manufacturing enables companies to combine internal and external resources. This allows companies to focus on Industry 4.0 capabilities for product innovation in joint efforts to develop products and complementary assets with more value-added (FRANK et al., 2019). The Industry 4.0 capabilities address in this research are: promoting coordination in the processes; developing a wide range of innovative products and processes; developing a high level of automation and autonomy for manufacturing machines, systems, and decision processes; digitalizing data collection and the connectivity infrastructure; developing operational and managerial processes-as-a-service; and developing a digital culture incorporating Industry 4.0 technologies at all employee levels (BUENO et al., 2020).

As previously discussed, researches prove the operational and financial benefits that practices and capabilities related to management approaches such as LM and Industry 4.0 provide for operations and supply chain management (OSCM). Then is important to study the interface of these management approaches with supply chain resilience (SCRE), in times of the greatest global disruption experienced since the Second World War (COVID-19 outbreak) (Brookings-Financial Times Tiger Index for the Global Economic Recovery TIGER, 2020). This thesis addresses the SCRE with the same perspective as Chowdhury and Quaddus (2017). These authors argue that supply chain management (SCM) is an important strategic organizational process for which resilience (or the lack thereof) must be performed following a structured path, after that corrective actions to identify and integrate appropriate resources are taken. SCRE is a multidimensional construct that can be measured by the following dimensions: proactive capability, reactive capability, and supply chain design quality (CHOWDHURY; QUADDUS, 2017). The SCRE key principles are: resilience can be built into a system in advance of a disruption; a high level of collaboration is required to identify and manage risks; agility is essential to react quickly to unforeseen events, and the culture of risk management is a necessity. Factors such as agility, availability, efficiency, flexibility, redundancy, velocity, and visibility also are important to resilience building (PETTIT et al., 2010; Christopher and Peck, 2004). The COVID-19 outbreak is an unprecedented and extraordinary crisis that makes evident the need for progressing supply chain resilience research and practices. The urgency for social distancing and quarantine culminated in a global disruption and vulnerability of SCs. Therefore, it evidences the urgency of designing a robust and resilient global supply chain (IVANOV; DOLGUI, 2020a).

1.2 RESEARCH RELEVANCE

Resilience has ultimately become enormously important in the supply chain domain because of the disruptions in the COVID-19 era. According to Chowdhury and Quaddus (2017), to build resilience, the supply chains need both proactive and reactive capabilities to adapt, integrate, and reconfigure during the pre-disaster and post-disaster phases surrounding disruptive events. Holling (1973), one of the pioneering researchers of resilience, defines resilience as the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between variables. During de COVID-19 outbreak the resilience has been studied in different aspects, there are studies about the role of supply chain risk management (SCRM) in mitigating COVID-19 effects on SCRE (BAZ; RUE, 2020; MARZANTOWICZ; NOWICKA; JEDLIŃSKI, 2020), about the lack of resilience in the food and beverage supply chain (CHENARIDES; MANFREDO; RICHARDS, 2021; CHOWDHURY et al., 2020; REJEB A.; REJEB K.; KEOGH, 2020), about the agility, resilience and sustainability perspectives integration during the COVID-19 pandemic (IVANOV, 2020b); the ripple effect of the COVID-19 outbreak in global SCs (IVANOV; DAS, 2020; IVANOV; DOLGUI, 2020c); viability in SCRE in times of COVID-19 crises (IVANOV; DOLGUI, 2020a); about digital supply chain twin for managing the disruption risks and resilience in COVID-19 times (IVANOV; DOLGUI, 2020b); about essential factors, barriers and enables which can help companies to overcome COVID-19 crisis and help companies to be resilient (KHURANA et al.2021; OKORIE et al., 2020); the importance of resilience, strategic agility, and entrepreneurship in the context of the fight against COVID-19 (LIU; M. LEE; C. LEE, 2020). The advent of the COVID-19 pandemic, declared by the WHO, culminated in extensive research investigating its impact on society, the environment, and organizations. Consequently, the convergence of management practices, like LM and Industry 4.0, with resilience approaches has emerged as a compelling and promising field of study.

LM has been a well-recognized strategy for organizations to achieve their goals. But during the COVID-19 crises, there is a discussion on the literature about the effectiveness of the just-in-time (JIT) system. According to Nandi et al. (2021), JIT is not a flexible system. This system tries not to have excess capacity and waste, limiting flexibility, which is an important aspect of agility. So it can harm the organization in times of crisis (SARKIS et al., 2020; BRYCE et al., 2020). On the other hand, Tortorella et al. (2020a) conducted a survey and the findings indicate that organizations that implemented lean services more extensively are also more likely to benefit from the effects that the COVID-19 had on work environments, especially in the case of a home office. According to Handfield, Graham, and Burns (2020) lean systems could be effective either in unpredictable demand, like in times of crisis. However, managers need to evaluate a supply chain against a range of possible threats and determine where to invest in inventory to provide the most flexibility and resilience at the lowest cost. Fonseca and Azevedo (2020) present the just-in-case approach, in which companies keep enough inventories to face supply and demand uncertainties and focus on balancing efficiency with flexibility, resilience, and reliability in the overall supply chain. Although there are a lot of studies that show a positive effect of LM on companies' performance (e.g., ZANON et al., 2020; NEGRÃO et al., 2020a; NOVAIS et al., 2020), studies related to LM and companies' responsiveness during the COVID-19 pandemic are scarce. This thesis intends to fill this gap in the literature by answering the following research question: What is the role of LM practices in improving companies' responsiveness in times of crisis?

To contain the spread of the COVID-19 disease, social distancing and quarantine were imposed on society and organizations. Studies focused on Industry 4.0 technologies have been developed to facilitate the routine of organizations and society in times of social distance. Akpan, Soopramanien, and Kwak (2020) in an SLR address the cutting-edge technologies for small business and innovation in the COVID-19 era. Almeida, Santos, and Monteiro (2020) in an SLR address the impact of digital transformation processes in three business areas: labor and social relations, marketing and sales, and technology. Ivanov and Dolgui (2020b) with a model explore the digital supply chain twin for managing the COVID-19 disruption risks and resilience in the era of Industry 4.0. Nandi et al.(2021) in an SLR address supply chains using blockchain-enabled circular economy and COVID-19 experiences. Besides research presents additive manufacturing and 3-D as a solution in times of crisis. Additive manufacturing could be used to create personal protective equipment to alleviate the shortage of such material during the early stages of the pandemic and to aid the very localized production of materials (AKPAN; SOOPRAMANIEN; KWAK, 2020; NANDI et al.,2021; RAPACCINI et al., 2020). Artificial intelligence (AI) can assist human decision-makers in making fast decisions. AI has great potential to assist human decision-makers in speeding up the decision-making process, especially in an emergency scenario where humans are under huge pressure (DWIVEDI et al., 2020). Although several studies are being developed addressing Industry 4.0 and the COVID-19 outbreak, none have yet presented empirical proof that smart capabilities can mitigate the COVID-19 effects on OSCM. This thesis intends to fill this gap in the literature by answering the following research question: Is the performance of manufacturing companies less impacted by the COVID-19 crisis when I4.0 is implemented?

Throughout history, the evolution of operations management has been parallel to the evolution of society and the market (GUNASEKARAN; NGAI, 2012). Therefore, the convergence of resilience with management approaches such as LM and Industry 4.0 emerges as just one of the focal points amid the COVID-19 pandemic. Ecological catastrophes, economic instability, drugs, corruption, terrorism, wars, and epidemics have all cast their shadows on societies, fostering diverse and distinct societal needs during these crisis times (SCHWANINGER, 2004). Throughout World War I, the industry experienced a significant transformation to meet the demands of the war, boosting in production of weaponry, ammunition, and military gear, bolstering industrialization across multiple nations. After the conflict, many war industries were redirected to civilian production, contributing to reconstruction and economic growth. During World War II, industry again converted to the war effort, with mass production of weapons, vehicles, planes, and military supplies. Massive production programs were implemented, driving technological innovation, and creating new strategies (HARRISON, 2005). After World War II, there was a surge in consumer demand, prompting companies to mass-produce standardized products. This led to the development of transfer lines and mass production systems. Subsequently, as customers sought higher quality at lower prices, companies adapted by implementing strategies like total quality management (TQM) and just-in-time (JIT) production systems (GUNASEKARAN; NGAI, 2012). Besides the war, the evolution of operations during health crises has been notable. Farooq et al. (2021) conducted a systematic literature review (SLR), highlighting advancements in logistics and resource allocation models to combat diseases such as Ebola, cholera, malaria, and smallpox. Then, amidst crises institutional changes challenging the status quo possible (GUNASEKARAN; NGAI, 2012). The literature underscores the evolution of operations management during crises, and the COVID-19 pandemic has been a recurring topic in publications that address the future of operations management. Now is the time to focus on the lessons from the pandemic, comprehending the advancements and emerging themes amid this major disruption in supply chains. This thesis intends to fill this gap in the literature by answering the following research question: What was the legacy of COVID-19 to operations management?

1.3 OBJECTIVES

The main objective of this thesis is to investigate the role of LM and Industry 4.0 during major breakdowns and present the legacy of COVID-19 on operations management.

To achieve it, three specific objectives were proposed:

Specific objective 1: Investigate the role of lean manufacturing (LM) to improve the company’s response in times of unprecedented crisis and in facing challenges in the post-COVID-19 world.

Specific objective 2: Investigate whether Industry 4.0 implementation improved companies’ resilience and whether companies’ performance maintained stability during the COVID-19 outbreak.

Specific objective 3: Present the emerging topics in literature during the pandemic and insights into the legacy of COVID-19 for operations management.

To achieve specific objectives 1 and 2, a survey will be carried out. To achieve specific objective 3 a Systematic Literature Review (SLR) and semi-structured interviews with industry practitioners will be carried out. The methodological release will be presented in the next section clarifying the next steps of the research being developed in this thesis.

1.4 METHODOLOGICAL RELEASE

The research methods choice in this thesis was associated with the scientific research development process and the details of each method are presented in the next chapters, which are organized in papers. Organizing the thesis in papers permits a streamline of the process of publishing research results. This thesis is composed of 3 papers. In two papers, the same research methods were applied, this may culminate in some repetition of the thesis text.

This thesis is classified as mixed-methods research. According to Bryman (2012), since 2001 it has become very popular among researchers in the social sciences. This term represents research that integrates quantitative and qualitative strategies in the same project.

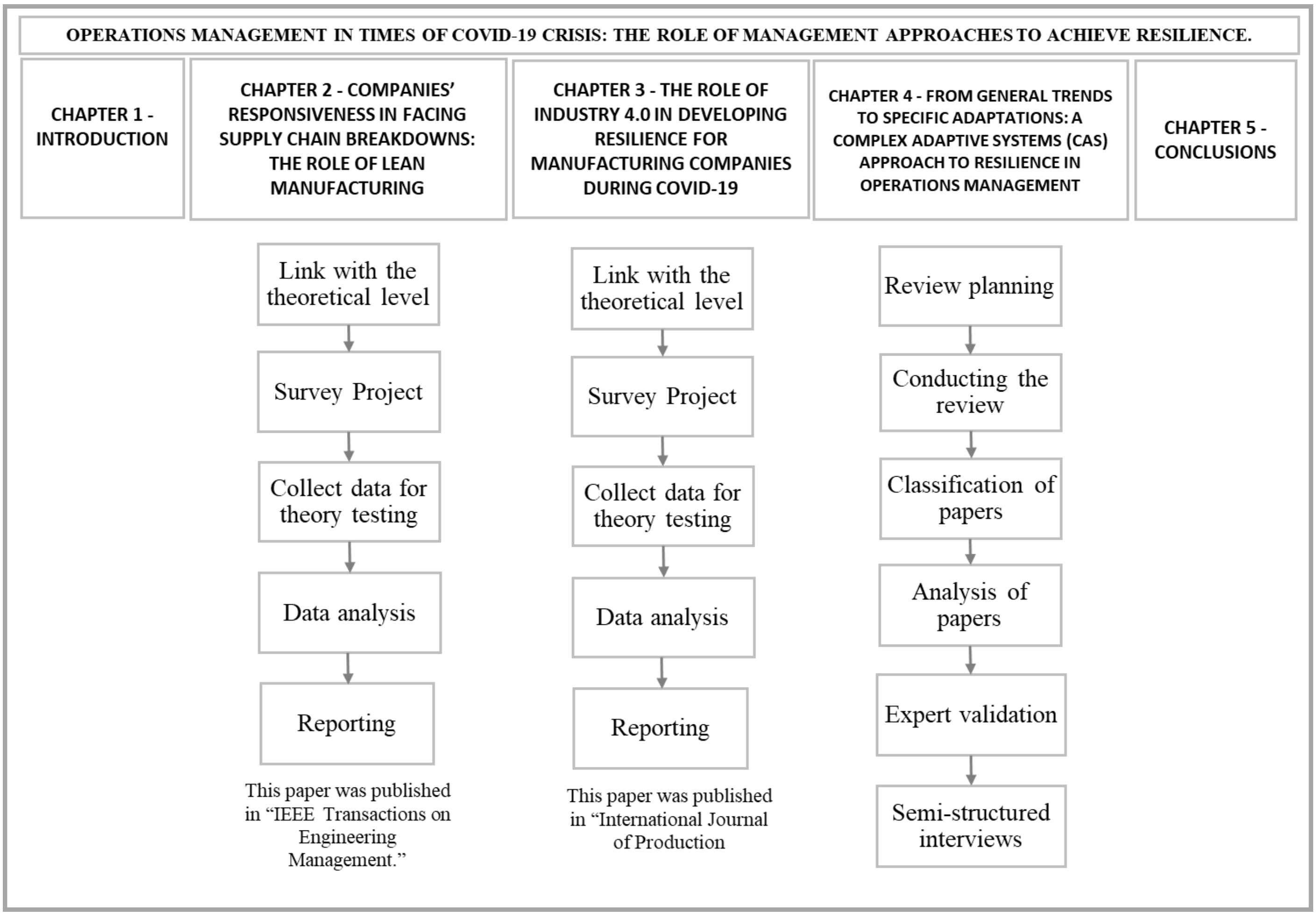
The quantitative research of this thesis was a Survey. Quantitative research is a strategy that emphasizes quantification in data collection and analysis. Therefore, it implies a deductive approach to the relationship between theory and research, in which the emphasis is on the testing of theories. It addresses the practices of the natural scientific model and positivism. The social reality is addressed as objective (BRYMAN, 2012). According to Forza (2002), a survey involves collecting information from individuals about the social units to which they belong. Thus, a survey research sampling process determines information about large populations with a known level of accuracy. This thesis developed an exploratory survey. An exploratory survey is suitable during the early stages of research on a phenomenon to gain preliminary insight into a topic and provide evidence for more in-depth research (FORZA, 2002).

The qualitative research of this thesis is a systematic literature review (SLR) and semi-structured interviews. Qualitative research is a strategy that generally emphasizes words rather than quantification in data collection and analysis. The inductive approach and theory generation are predominant in this strategy (BRYMAN, 2012). Pizzinatto and Farah (2012) affirm that qualitative research favors obtaining in-depth non-quantitative data on a given topic of interest. There is no intention of using statistical procedures for results analysis. As for exploratory research, Gil (2002), determines that the main objective is the improvement of ideas or discovery of intuitions, in a flexible way, which allows the consideration of the most variable aspects related to the studied fact. In social research, a literature review process is a fundamental tool. The objective is to allow the researcher to map and assess the state of the art and specify a research question for the evolution of knowledge (DENYER; TRANFIELD, 2009).

1.5 RESEARCH STRUCTURE

The thesis structure followed the logic of knowledge development. The methods applied will be better addressed in the next chapters, which were structured in papers. The first chapter contains an introduction, to clarify which subjects and methods will be covered in the research. In the second chapter, the first paper will be presented, which consists of the first survey of the thesis. Which studies the role of LM in helping organizations to face the COVID-19 outbreak. The third chapter contains the second paper and survey. Which studies the role of Industry 4.0 in helping organizations to face the COVID-19 outbreak. The fourth chapter contains the third paper. This paper concludes the thesis because summarizes the COVID-19 pandemic in operations management. The research presents a systematic literature review of the legacy of COVID-19 for operations management and semi-structured interviews with industry practitioners. The first and second papers in this thesis focus on companies' responsiveness during the most critical period of the pandemic and the disruption of supply chains. The third article addresses the legacy of COVID-19 for operations management. It is based on emerging themes from the pandemic and the perspectives of practitioners in the industry in a post-COVID-19 world, where the lessons learned constitute the main legacy. The fifth chapter contains the conclusions, practical implications, research limitations, and suggestions for future research. Figure 1.1 shows the research structure.

Figure 1.1 Research structure



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CHAPTER 2 COMPANIES' RESPONSIVENESS IN FACING SUPPLY CHAIN BREAKDOWNS: THE ROLE OF LEAN MANUFACTURING

In this chapter, the first thesis paper will be presented. This paper is a survey about the role of LM in helping organizations to face the COVID-19 outbreak. This paper has already been published in the journal "IEEE Transactions on Engineering Management" (DOI: 10.1109/TEM.2023.3286352).

ABSTRACT: Crisis times result in supply chain (SC) instabilities but represent a unique opportunity to test organizational theories and measure the effectiveness of management approaches in exceptional times. The main goal of this research is to study the role of lean manufacturing (LM) to improve the company's response in times of unprecedented crisis and in facing challenges in the post-COVID-19 world. A survey was conducted with 202 manufacturing companies and then analysed using structural equation modelling. Our main findings suggest that LM's excellence is not lost during crisis times and that the performance of lean companies can be sustained during crises. Lean companies have a culture of problem-solving and innovation that makes them more responsive during periods of crisis and better prepared for changes and challenges in a post-crisis world. To the best of our knowledge, this is the first study that provides empirical evidence that LM practices are a moderating variable that improves companies' responsiveness in crisis times.

Managerial relevance statement: The main managerial contribution of the study is to present LM for companies as a philosophy that goes beyond continuous improvement. LM has the potential to provide companies with the tools necessary to overcome future crises and disruptions, promoting responsiveness. Our research shows that lean companies, in addition to facing the COVID-19 outbreak more efficiently, through their organizational culture open to changes and innovations, are committed to the development of efforts to face the challenges in a post-COVID-19 world. Therefore, our research proves that long-term investments in practices and tools aligned with excellence bring benefits not only to the companies' routine but also in times of unprecedented crisis and post-disruption challenges.

Keywords: Crisis times; Lean manufacturing; Structural equation modelling; Responsiveness; COVID-19.

2.1 INTRODUCTION

The World Health Organization (WHO) (2023) declared the novel coronavirus SARS-CoV-2 (COVID-19) pandemic on 11 March 2020. Aiming at "flattening the contagion curve", social distancing has become part of the daily lifestyle for individuals, governments, communities, industrial firms, and academic institutions (SARKIS et al., 2020). Quarantine and social distancing have had several effects on organizations and their supply chain (SC). Thus, companies have needed to adapt their production system to maintain productivity and avoid collapse.

Several types of research have addressed the effects of COVID-19 on companies. Some examples of these effects are: a sudden change in supply concerning products; a sudden change in demand for products and consumer behaviour; a home-office work environment; job insecurity; virtual connection; workforce shortages; financial problems; proper sanitation of the company; intellectual property challenges; loss of contracts or sales; and limited capabilities concerning human, technological, and managerial aspects due to limited resources and access (SARKIS et al., 2020; BIANCO et al., 2023; BRYCE et al., 2020; IVANOV; DOLGUI, 2020; KUMAR et al., 2020; KUCKERTZ et al., 2020; MOTA et al., 2022; QUEIROZ et al., 2020; TIETZE et al., 2020). The effects of COVID-19 on operations management have highlighted the vulnerability of SCs and the need to adopt management approaches aligned with responsiveness, which could help companies maintain performance even in times of crisis. We argue that Lean Manufacturing (LM) is one of those approaches, once is aligned with operational excellence. Therefore, the main goal of our study is to investigate whether the operational excellence achieved through LM provides responsiveness for organizations when facing the current crisis and the commitment to develop efforts to face future challenges in a post-COVID-19 world. We agree with Boccaletti et al.'s (2020) claim that there is an immediate need for the scientific community to come together and provide novel and better methods, strategies, forecasting techniques, and models to understand and mitigate the effects of the present and future world crises

Analysing the results of some classic studies in the literature (WHITE et al., 1999), as well as those of other more recent studies (NEGRÃO et al., 2020a;, NEGRÃO et al., 2020b), it is clear that organizational performance improves by adopting LM. Although many studies have shown a positive effect of LM on companies' performance, empirical studies related to LM and the COVID-19 pandemic are scarce. Our research intends to fill this literature gap. Ardolino et al. (2022) point out that it is important to balance lean practices and resilience in manufacturing and SCs, so in the context of the COVID-19 pandemic is necessary to investigate the costs of building resilient production while allowing for some extra cost to strengthen manufacturing systems. Tortorella et al. (2020) conducted a survey, and the findings indicated that organizations that implemented lean services more extensively were also more likely to benefit from the effects that COVID-19 had on work environments, especially in the case of a home-office working environment. According to Pujawan and Bah (2021), the reduction of lead time is essential in times of crisis because it improves responsiveness and, at the same time, supports the idea of lean thinking that attempts to minimize waste or nonvalue-added activities. The survey result developed by Mishra et al. (2021) about SMEs suggests that during COVID-19, the Lean Six Sigma tools improve manufacturing operations, quality, productivity, cost reduction, and safety. The authors point out that Lean Six Sigma enables learning and training that can improve the skills of companies and the companies' reputation to customers and all stakeholders. On the other hand, Sarkis et al. (2020) and Bryce et al. (2020) criticized LM and just-in-time (JIT) regarding organizations' responses to the effects of COVID-19.

We base our study on both the Excellence Theory (ET) and Reinforcement Theory (RT). According to Kessler (2013), when something is excellent, it is assumed that it is in the state of quality, the condition of excelling, or the state of superiority. The Toyota Production System (TPS) is a well-known model of excellence in operations management. The present study will delimit excellence to operational performance (KESSLER, 2013). Our research intends to ascertain whether it is true that the operational excellence achieved by LM is not lost in times of crisis. In other words, we aim to examine whether LM practices moderate the COVID-19 effects on companies' responsiveness, showing that lean companies are more responsive. Further, our research studies the influence of responsiveness and LM practices on companies' commitment to developing efforts to face future challenges and SC breakdowns in the light of the RT of Kessler (2013). RT explains the hypotheses related to future challenges. In this way, the organizational learning developed during the COVID-19 crisis, together with the positive results achieved during the pandemic act as reinforcers to facilitate the development of efforts to face future crises and prepare companies for the post-COVID-19 world. ET and RT are complementary to explain the hypotheses model that we are proposing.

Based on the above discussion, the following research question (RQ) arises:

RQ. What is the role of LM practices in improving companies' responsiveness in times of crisis?

The present study conducted a survey of 202 Brazilian manufacturing companies to investigate this question. Brazil is among the emerging economies most affected by COVID-19, with 701,833 confirmed deaths reported to WHO until 11 May 2023. The collected data were examined by applying multivariate data analysis techniques. LM implementation was measured using the model proposed by Shah and Ward (2007), which considers 10 LM practices. The company's response to the COVID-19 outbreak was measured using the resilience practices proposed by Chowdhury and Quaddus (2017). COVID-19 construct questions were developed from papers addressing the effects and future challenges of the COVID-19 outbreak in manufacturing operations management (SARKIS et al., 2020; BRYCE et al., 2020; IVANOV; DOLGUI, 2020; KUMAR et al., 2020; KUCKERTZ et al., 2020; QUEIROZ et al., 2020).

The remainder of this article is structured as follows. In Section 2, we explore and highlight the gaps in the literature and present our research hypotheses. Section 3 describes the research method adopted. Sections 4 and 5 present and discuss the results, respectively. Finally, Section 6 presents the conclusions of our research, the theoretical and practical contributions, and also the limitations that may motivate future studies.

2.2 THEORETICAL BACKGROUND AND HYPOTHESES DEVELOPMENT

2.2.1 The COVID-19 outbreak and its impact on business performance

Araz et al. (2020) claimed that the COVID-19 outbreak is one of the major disruptions encountered over recent decades. In a report published on 21 February 2020, Queiroz et al. (2020) mentioned that Fortune (2020) indicated that 94% of the companies listed in the Fortune 1000 were facing SC disruptions due to COVID-19. The impacts of COVID-19 on SCs have drawn the operations and supply chain management (OSCM) community's attention. Some recent research on this theme includes that of Yang et al. (2022), Ivanov (2020), and Sarkis et al. (2020), among others.

Disruptions to the SC due to changes in consumer behaviour and, consequently, an increase or decrease in demand for various products and/or services impact companies' inventory (SARKIS et al., 2020; IVANOV; DOLGUI, 2020; KUMAR et al., 2020; BEHL et al., 2022). Besides inventory issues, increased lead times were also a problem being faced by companies. Having disruptions in supplier nodes or problems with workforce shortages and a lack of flexibility to face those issues (KUMAR et al., 2020; VERMA; GUSTAFSSON, 2020), companies struggled to deliver goods within promised deadlines. Therefore, delivery performance has been dramatically affected (AKPAN et al., 2022; FONSECA; AZEVEDO, 2020).

Although the literature has pointed out that SCs, in general, have been negatively affected by the COVID-19 outbreak, leading to a drop in sales and a lack of supplies for production, some business models have benefited, such as the production of hygiene products and personal protection products (e.g. masks). The aim of the present research, however, is to consider only companies negatively affected by the pandemic to better fit the hypothesis model. Therefore, to verify whether the companies participating in the sample in the present study are indeed part of chains negatively affected by the COVID-19 outbreak, we formulate the following hypothesis:

H1: The COVID-19 outbreak harm companies' performance.

2.2.2 The Excellence theory and relationship between LM, companies' responsiveness, and performance stability in crisis times

In the famous book *In Search of Excellence – Lessons from America's Best-Run Companies*, Peters and Waterman's (1982) results suggested that all excellent companies are brilliant at doing the basics. To be excellent, companies must work hard to keep things simple in a complex world. It is necessary to persist, insist on top quality, listen to customers, pursue innovation and motivate employees.

According to Talwar (2011), the excellence models provide a direction to achieve sustainability in terms of profits, people, and planet development. The term excellence has been defined and used in various contexts and fields during the long history of humanity, and there are also different excellence models in literature (TALWAR, 2011). In operations management, one crucial excellence model is the TPS (KESSLER, 2013), which emerged in the 1950s. Since the 1980s, LM, which originated from TPS, has spread worldwide as a philosophy. Western organizations have also adhered to LM (WOMACK et al., 1992). Central to the concept of operational excellence is outperforming in terms of operational performance, such as increased customer satisfaction, improvement in quality and productivity, lead time reduction, decreased inventory, and increased operating profits. Further, companies must continue progressing from a current state to an improved state towards operational excellence (FOUND et al., 2018).

LM has been a well-recognized strategy for companies to achieve performance improvement and excellence (NEGRÃO et al., 2020a; WIENGARTEN et al., 2015). Some research corroborates the positive aspect of LM on performance even during the COVID-19 outbreak. For example, Verhulsdonck and Shash (2021) discussed the role of lean principles in creating data dashboards with actionable metrics focusing on several stakeholders. Rashad and Nedelko (2020) proposed a framework with lean, agile, and lean-agile principles. The same was done by Ivanov (2020), who proposed viable SC models based on lean principles. Dorofeev et al. (2020) designed several actions based on lean transportation principles to ensure better integrity of transportation and logistics. Reshad et al. (2020) shows an application of the DMAIC cycle to improve testing results during the COVID-19 outbreak.

However, during the pandemic, it has been argued that LM and JIT have failed because the focus on low inventory and total waste elimination did not allow companies to react to higher demands, causing disruptions in SCs and the ripple effect (BRYCE et al., 2020). Fonseca and Azevedo (2020) discussed a new strategy called “just in case”, in which companies can keep enough inventory (safety stocks) to handle events similar to what happened during the COVID-19 outbreak.

This debate and the fact that none of the studies have presented empirical evidence concerning the moderating role of LM in the relationship between the COVID-19 outbreak and companies' responsiveness represents an interesting gap in the field. Our intention with this research is to verify that, once achieved through LM (practices implemented before COVID-19), operational excellence is not lost in times of crisis. This would demonstrate that lean culture allows companies to remain more robust and more responsive during the COVID-19 outbreak. Thus, the greater the COVID-19 effect on the company, the more responsive the company will be in the presence of the moderating variable LM. Therefore, we have the following hypothesis: *H2:* The level of LM in companies moderates the relationship between the COVID-19 effects and companies' responsiveness.

According to Ivanov and Das (2020), epidemic outbreaks have multiple and interactive impacts on the SC. Traditional SC resilience practices, such as holding risk mitigation inventory for several weeks or having subcontracting facilities, might require adaptations. Proactive measures, such as inventory hoarding, can help only at the beginning of an epidemic due to the potential for long disruption times. Similarly, backup suppliers and subcontracting facilities would be simultaneously or gradually impacted by regional, national, or continental lockdowns and quarantines. Therefore, authors have shown that the focus of SC resilience management, while considering epidemic outbreaks, should shift towards situational responses to real-time changes rather than building proactive redundancies. When companies were confronted with the unprecedented threats of the COVID-19 situation, they were forced to “improvise” new risk assessment and processing measures. The combination of SC practices contributed to generating a positive impact of SC risk control on SC robustness (BAZ; RUEL, 2020). The case study developed by Vanany et al. (2021) showed that two variables in the response and recovery SC dimension identified in the literature were essential. These were quick responses and communications with the government. The ability to respond and recover during disruption is crucial, especially for achieving an equilibrium between supply and demand, and this ability is necessary for developing SC resilience. Previous literature presents some capabilities that contribute to responsiveness in times of crisis, such as Margherita et al. (2021) which showed that digital technologies were important for company responses to COVID-19 and Bag et al.

(2021) argued that high innovation leadership increases the effect of big data analytics capabilities on responsiveness.

According to Chowdhury and Quaddus (2017), operational vulnerability and SC performance can be forecasted based on adopting resilience practices. Over the past two years, the SC had been vulnerable because of the COVID-19 outbreak. Considering the relationship between SC performance and disasters that directly affect humanity, Altay et al. (2018) showed that SC resilience significantly affects post-disaster performance, considering organizational culture as a moderating variable. According to Magableh (2021), SC resilience depends on the capability of rearranging resources to control disruptions. In pandemic times, collaborative activities, such as information sharing, SC connectivity, communication (DUBEY et al., 2017) and the use of digital technology (IVANOV, 2021a) enhance SC resilience by improving visibility, quickness, flexibility, and, consequently, the company's response to the crisis.

Based on these previous literature, we propose the following hypothesis:

H3: The greater the company's responsiveness, the less the deterioration in performance.

2.2.3 The Reinforcement theory and the company's commitment to develop efforts to face future challenges

RT is a learning theory. It is based on the principle that a relatively permanent behaviour change is achieved through reinforced practice or experience. RT is often referred to as operant learning and serves as the basis for organizational behaviour modification (KESSLER, 2013). RT's basic premise is that the causal agents of the action are found in the relationship between antecedents, behaviour, and consequences (A-B-C), so this theory is suitable for our research. We intend to show that organizational learning during the COVID-19 outbreak will facilitate companies' commitment to developing efforts to face future SC breakdowns. In the present research, the COVID-19 outbreak is the “antecedent”, the desired “behaviour” (companies' responsiveness) relates to the environmental conditions (LM practices), and the “consequences” act as reinforcers towards behaviours to deal with future SC breakdowns. The principle is that behaviour increases in strength when followed by a reinforcer (KESSLER, 2013).

According to Villere and Hartman (1991), RT has profound consequences for managers, since behaviour with positive consequences will be repeated, while behaviour with negative consequences will cease. We intend to show that if the maturity in lean practices and companies' responsiveness has helped to face the COVID-19 outbreak, this behaviour would be repeated in the future. Therefore, it will be easier for lean and responsive companies to be committed to the development of efforts to overcome future challenges. This is supported by Peschl (2021) who pointed out that past experiences and already existing knowledge often drive classic organizational learning and forms of innovation.

The literature has pointed out lessons and challenges that must be addressed in a post-COVID-19 world. Habicher et al. (2022) discussed challenges from a societal perspective and offered a future-oriented policy instrument for political, economic, and civil actors and key stakeholders. Kumar et al. (2020) argued that Industry 4.0 could be a significant driver for reducing the impact of challenges in fighting the COVID-19 outbreak. Bryce et al. (2020) pointed out that organizations will need to establish a business model focusing on innovation, diversity, flexibility, and the ability to work across boundaries to encourage new and adaptive approaches in the face of adversity, and to identify changes in consumers' buying patterns after the COVID-19 pandemic (KUMAR et al., 2020). Some authors have also reported the viability and resilience of the SC as a significant challenge to be faced in a post-COVID-19 world, and responsiveness is an important aspect of resilience, as it helps organizations adapt and overcome challenges in a timely and effective manner (BRYCE et al., 2020;, IVANOV; DOLGUI, 2020).

Being responsive means focusing not only on today but on the challenges and events that may occur in the future. Responsiveness is an ideal construct for measurement in times of crisis, but it could also be developed in stable times with long-term thinking. When the company is preparing to be able to respond quickly to fluctuations in supply and demand, it is preparing for an uncertain future. Therefore, based on the RT , which points out that a consequence acts as a reinforcer after the behaviour is performed, we intend to show that responsive companies learn in times of crisis and will tend to be committed to develop efforts to face future crises even more robustly (KESSLER, 2013). According to Hosseini et al (2020) SC resilience could be understood as an open system that evolves over time in an adaptive matter through balancing vulnerabilities and capabilities in the SC. The authors suggest an approach to SC disruption risk and the ripple effect from a holistic perspective that considers the capacity of the mutual intersections of risk mitigation and recovery capabilities to enhance each other based on the synergetic effects of SC resilience. Based on the literature concerning RT, we propose the following hypothesis:

H4: Companies' responsiveness positively affects the companies' commitment to developing efforts to face future challenges (SC breakdowns).

According to Liker and Ballé (2013), the main principle in LM is the spirit of “challenge”. Posing a challenge, providing support, questioning, providing needed resources, and letting employees struggle is the main way of developing people. LM requires an organization to establish a continuous learning and improvement culture that offers and prepares employees for autonomy to deal with possible production disruptions. The post-COVID-19 world will present several challenges for companies, which will be better faced if companies are open to innovations and changes.

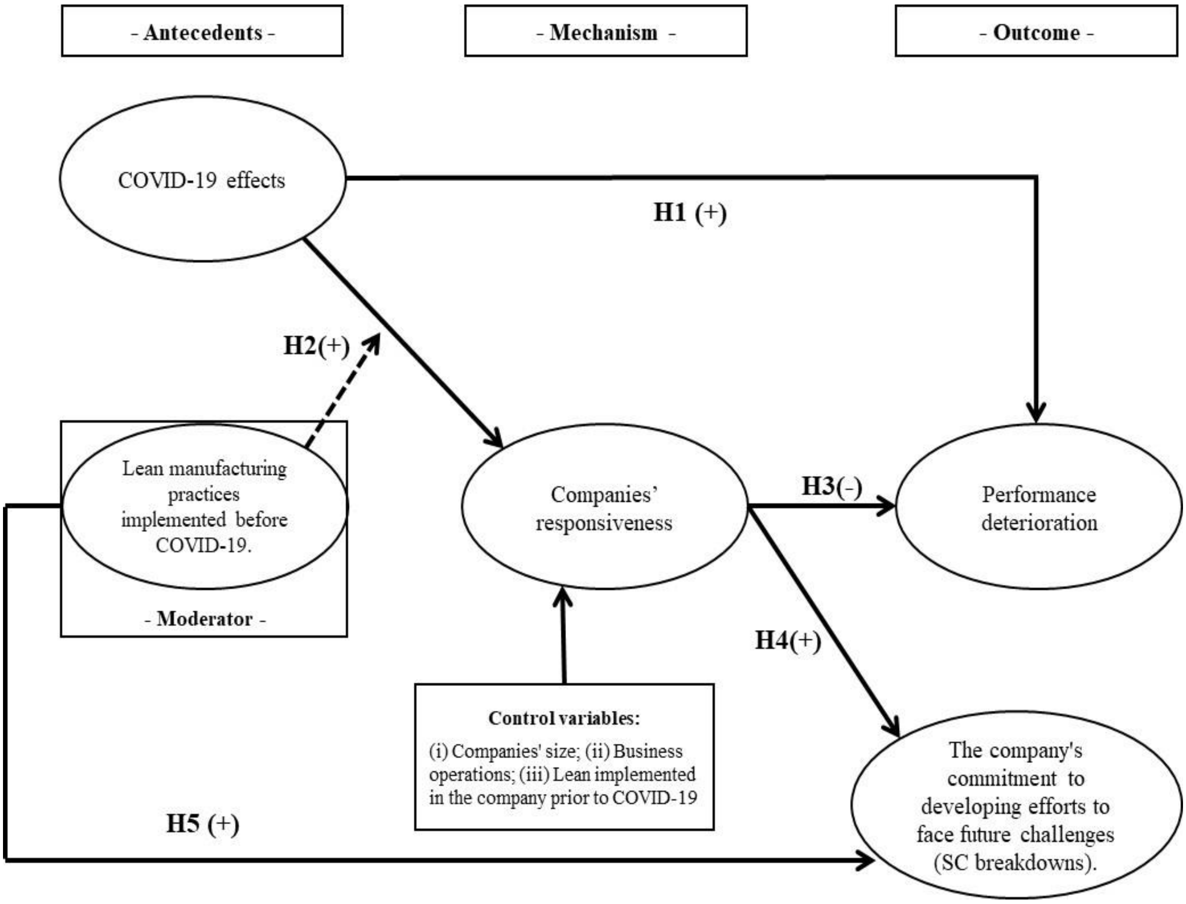
Even before the COVID-19 outbreak, lean organizations insisted on cleanliness and safe health conditions in the work environment. One of the main challenges reported in the literature is the development of policies and strategies aimed at the health and safety of employees and the awareness of employees regarding the need to maintain a clean work environment, encompassing distancing and the use of a mask for personal protection (Kumar et al., 2020). Lean culture was already preaching similar values even before the spread of COVID-19. Therefore, lean organisations are believed to be more committed to developing efforts to face this challenge in a post-COVID-19 world.

Many studies have shown that lean organizations are better prepared for changes and innovations. Möldner et al. (2020) suggested that both technical and human lean practices have a moderate to a strong positive impact on the input and occurrence of incremental and radical process innovation in manufacturing organizations. We agree with Peschl (2021), who asserted that organizational learning must be aligned with the future, integrating learning and innovation processes. Based on RT and the literature about the positive relationship between LM and innovation, we propose the following hypothesis:

H5: The level of LM in the company positively affects the companies' commitment to developing efforts to face future challenges (SC breakdowns).

The final research model is presented Fig. 2.1. Appendix A provides a detailed list of the assertions that constitute each of the constructs depicted in Fig. 1. The hypotheses proposed were based on previous literature and organizational theories as discussed in the previous sections. We have no intention of testing the direct impact of LM on companies' performance, as there is vast literature on this subject. The originality of our research is to study the LM as a moderating variable. So we intend to show that in times of a pandemic, it is not Lean tools that directly improve performance but the companies' response to the crisis.

Figure 2.1 - Research model



2.3 RESEARCH METHOD

2.3.1 Data collection procedures

The population of this study is concentrated in the Brazilian manufacturing industry, which was negatively affected by the COVID-19 outbreak. According to the contagion curve in emerging economies, Brazil is among the most affected with 710,833 confirmed deaths reported to WHO until 11 May 2023, reinforcing the sample fit (TORTORELLA et al., 2021a). Given the significant impact of COVID-19 on Brazil, studying the impact of the pandemic on industries in the country can provide valuable insights for policymakers, researchers, and practitioners worldwide. Besides, manufacturing companies in Brazil are in general familiar with LM (NEGRÃO et al., 2020a; NEGRÃO et al., 2020b). In addition, companies in Brazil were highly impacted by COVID-19, experiencing issues with a shortage of raw materials and a lack of capacity (BIANCO et al., 2023). Therefore, applying our research considering this unit of analysis seems appropriate. The questionnaire was administered using the SurveyMonkey platform, and the link was sent to the companies' e-mails between October and December 2020.

One month after sending the questionnaire link to the companies, another email was sent to remind them that the team of researchers was waiting for the questionnaire to be properly answered. The same procedure was repeated, constantly attaching the link to the questionnaire, following recommendations for Internet research methods (DILLMAN, 2000). By December 2020, 202 questionnaires had been fully completed and were considered valid for the survey, after analysing the responses using the standard deviation (standard deviation of responses >0) and outliers. The final sample was 202 questionnaires. Our study is exploratory and not intended to make generalizations. As we don’t aim at generalizations, our main concern is to have a sample size adequate to apply the SEM method. Literature on this method addresses that a sample needs to have at least 100 cases (LATAN et al., 2017). In our research, the sample is 202. Besides ‘10-times rule’ method has been a favorite approach for sample size, it builds on the rule that the sample size should be greater than 10 times the maximum number of inner or outer model links pointing at any latent variable in the model (KOCK; HADAYA, 2016; Hair et al., 2011). Our study also meets this criterion. It also satisfies the rule defined by the minimum R-squared method (HAIR et al., 2017). On the other hand, through simulations, Kock and Hadaya (2016) suggest the inverse square root and gamma-exponential methods as more accurate for determining the sample size. However, these methods depend on the smallest path value (β) present in the model to estimate the sample size. Hair et al. (2021) warn that methods that disregard the size of the more complex regression, and analyze only the lowest path value present in the model, can result in very large samples, especially if the model has a path with low or nonsignificant loading, overestimating the sample size. For this reason, we have chosen not to base the sample size on the inverse square root and gamma-exponential methods, as the model in the article is exploratory in nature, in which the significance and size of the relationship between latent variables are still being examined through hypotheses. Moreover, we also consider the sample size to be adequate once it is similar that of other large-scale research studies in operations management (BIANCO et al., 2023; NEGRÃO et al., 2020b; TORTORELLA et al., 2020; ALTAY et al., 2018; COSTA et al., 2021).

2.3.2 Characteristics of companies and respondents

The characteristics of the companies surveyed are shown in Table 2.1. In total, 21 manufacturing industry sectors were mapped, predominantly for food and beverage manufacturers (68%). Moreover, 84% of the surveyed companies are considered large (more than 100 employees).

Table 2.1- Characteristics of the companies.

Industrial sector	**n**	**%**	**Lean practices**	**n**	**%**	**Employees**	**n**	**%**
Food and beverage products	138	68	Less than 2 years	100	49.5	To 10	2	1
Cellulose and paper	9	4	Between 2 and 5 years	55	27.2	11 to 50	14	7
Wood products	7	3	More than 5 years	47	23.3	50 to 100	17	8
Auto-vehicles	7	3				More than 100	169	84
Chemical products	5	2						
Non-metallic mineral products	5	2						
Others	31	15						
Total	202	100	Total	202	100	Total	202	100

The respondents' profiles are shown in Table 2.2. A total of 35% of respondents occupy managerial positions and 46% supervision, and 80% of these professionals have worked in these companies for more than five years. The respondents were qualified to complete this survey based on these characteristics.

Table 2.2- Characteristics of the respondents.

Occupation	n	%	Occupancy time	n	%
Manager or Director	70	35	Less than 5 years	39	20
Supervisor or Coordinator	93	46	More than 5 years	163	80
Others	39	19			
Total	202	100	Total	202	100

2.3.3 Measures

The research instrument used in this study was structured in six parts (see Appendix A). The first part asked about organization and respondent data. The second part verified the degree of adopting lean practices in the studied companies using Shah and Ward's (2007) scale. In the third and fifth parts, we evaluated the organization's perception of the COVID-19 effects and the companies' commitment to developing efforts to face the post-COVID-19-world challenges and future SC breakdowns. The COVID-19 construct questions were developed from papers addressing the effects and future challenges of the COVID-19 outbreak in manufacturing operations management (SARKIS et al., 2020; BRYCE et al., 2020; IVANOV; DOLGUI, 2020; KUMAR et al., 2020; KUCKERTZ et al., 2020; QUEIROZ et al., 2020). The fourth part evaluated the organization's perception of companies' responsiveness to overcome the COVID-19 outbreak. This dimension was adapted from the resilience model practices proposed by Chowdhury and Quaddus (2017). The sixth part addressed manufacturing companies' performance during the COVID-19 outbreak; this construct was developed following Costa et al. (2021). Most of the statements were answered on a seven-point Likert scale that ranged from (1) “Fully disagree” to (7) “Fully agree”.

2.3.4 Robustness checks

According to n Bryman (2012), the most prominent criteria for evaluating social research are reliability and validity. In quantitative research, reliability is concerned with the question of whether a measure is stable or not. Validity is concerned with the integrity of the conclusions that are generated from a piece of research. Below are the criteria that ensure the reliability and validity of our research:

1. Research instrument validity and reliability: The questionnaire was based on previously published scientific articles and based on a validated questionnaire applied in Costa et al. (2021) research. The statements are direct and carefully formulated, ensuring the respondent's understanding. During the research instrument elaboration, several validation rounds were carried out with 4 experts in operations management with extensive practical and theoretical knowledge.

2. Data collection validity and reliability: There was no direct contact between the respondents and the researcher during data collection. In addition, a random sample was used to avoid any bias in data collection. Data collection was during the height of the COVID-19 pandemic, so the questionnaire was answered by employees who were experiencing the difficulties of the pandemic in practice. Most respondents held leadership positions which assures a global understanding of the situation of the company/SC.

3. Hypothesis model validity and reliability: The hypothesis model proposed in our research was based on previously published scientific articles. Two organizational theories (ET and RT) comprise our propositions' theoretical foundation. The hypothesis model was validated statistically. Besides, 4 operations management experts with extensive practical and theoretical

knowledge validated the model. The triangulation between literature, statistical analysis, and experts ensure the validity and reliability of our research.

4. Statistical robustness: To ensure the validity, reliability, and robustness of the proposed hypothesis model, we performed the most indicated static tests in the literature for these purposes. Statistical analyzes will be presented in detail in section 4. Section 4.5 contains the supplementary analyzes that were performed to ensure the robustness of the model, including nonlinearity, endogeneity, and unobserved heterogeneity (SARSTEDT et al., 2019).

2.4 DATA ANALYSIS

Partial least squares structural equation modelling (PLS-SEM) was considered the most appropriate technique for data analysis and testing the hypotheses to provide empirical findings for our research. The PLS-SEM technique is suitable for assessing complex models, such as models with formative or composite constructs, mediation effects, and moderation effects (BECKER et al., 2018). Given the nature of the constructs in this study, which are formative or composite, and the model's complexity, PLS-SEM is considered an appropriate technique (LATAN et al., 2017; HENSELER, 2021; MEHMETOGLU; VENTURINI, 2021). Furthermore, according to Lim et al. (2021), this approach has useful supplementary analyses (i.e. examining endogeneity, non-linearity, and unobserved heterogeneity). Our research follows the steps for data analysis proposed by Sarstedt et al. (2019). We used SmartPLS software to estimate the proposed model and test the hypotheses (LIM et al., 2021).

2.4.1 Non-response bias

We tested for non-response bias to be sure that the respondents in our study sample represent the population under analysis (VOGEL; JACOBSEN, 21021). This bias is a threat in our survey method, given that the sample was determined randomly and not purposefully. We used two approaches to detect this bias. First, we compared early versus late responders. We found no difference between the two sample groups based on the *t*-test (p>0.05) for each variable in the model. Therefore, we conclude that this bias does not occur. To legitimate this result, we compared those who never refused to participate in the survey with those who initially declined (FULTON, 2016). Again, we found no difference between the two groups based on the *t*-test (p>0.05); therefore, we conclude that our data are free from this bias.

2.4.2 Common method variance (CMV)

CMV usually arises when the same respondent attributes numerical values on a psychometric scale, both for the antecedent constructs (e.g. COVID-19 effects) and consequence constructs (e.g. performance deterioration) (SPECTOR et al., 2019). Thus, it is essential to adopt procedures that avoid CMV. In this study, we reduced this bias by sorting the items randomly for each construct. We also explained to each respondent that his/her name and company information would be kept anonymous.

The collinearity approach recommended by Hair et al. (2017a) was used to evaluate potential adverse CMV effects statistically. As shown in Table 2.3, the collinearity assessment produced variance inflation factor (VIF) values between 1.379 and 3.983, which is less than 5, suggesting CMV is not likely to be an issue (HAIR et al., 2017a).

Table 2.3 Results of the measurement model and collinearity

Constructo	Loading	Loading	alpha	rhoA	CR	AVE	Outer VIF	Outer Weight
Lean manufacturing practices (LMP)			0.913	0.915	0.928	0.563		
Suppfeed	0.723	0.722					2.105	0.116
SuppJIT	0.765	0.766					2.740	0.138
Suppdvt	0.764	0.767					2.696	0.119
Custinv	0.725	0.722					1.869	0.132
Pull	0.661	0.668					1.775	0.126
Flow	0.779	0.779					2.492	0.142
Setupred	0.764	0.760					2.488	0.129
SPC	0.797	0.795					2.432	0.130
Empower	0.774	0.773					2.103	0.150
TPM	0.742	0.743					2.071	0.150
COVID-19 effects on companies (CEC)			0.904	0.915	0.929	0.725		
Sectaffe	0.888	0.887					3.524	0.247
Compaffe	0.916	0.917					3.983	0.274
Suppaffe	0.781	0.775					1.846	0.200
Compeaffe	0.881	0.882					3.044	0.231
Demaffe	0.782	0.787					2.004	0.217
Companies' responsiveness (CR)			0.864	0.868	0.896	0.551		
Suppdisr*	0.583	-					-	-
Proddeli*	0.511	-					-	-
Demachan*	0.669	-					-	-
Capacons*	0.516	-					-	-
Physdist	0.722	0.732					2.215	0.206
Finacons	0.700	0.717					2.065	0.208
Provheal	0.714	0.782					2.015	0.206
Workremo	0.625	0.714					1.767	0.168
Criscomm	0.620	0.685					1.891	0.157
Orgaresp	0.765	0.812					2.267	0.212
Digitech	0.695	0.745					2.019	0.187

Constructo	Loading	Loading	alpha	rhoA	CR	AVE	Outer VIF	Outer Weight
Reduwast*	0.637	-					-	-
Mansysc*	0.765	-					-	-
The company's commitment to developing efforts to face future challenges (SC breakdowns) (FC)			0.853	0.858	0.896	0.633		
Adopind4.0	0.725	0.709					1.481	0.231
Deveresi*	0.845	-					-	-
Deveheal*	0.808	-					-	-
Buyipatt	0.802	0.793					1.975	0.244
Flexresp	0.850	0.869					2.581	0.272
JITSupp	0.782	0.839					2.151	0.263
Mainprod	0.707	0.759					1.715	0.244
Performance deterioration (PD)			0.858	0.872	0.889	0.503		
Prodaffe	0.690	0.732					1.803	0.204
Finaperf	0.738	0.777					2.845	0.219
Globperf	0.715	0.760					2.526	0.198
Capaavai	0.758	0.782					2.047	0.201
Prodquali*	0.511	-					-	-
Wastincr	0.600	0.567					1.379	0.101
Proddefe*	0.539	-					-	-
Delaincr	0.716	0.684					2.711	0.137
Leadtime	0.736	0.724					2.765	0.166
Shormate*	0.557	-					-	-
Invedecr	0.632	0.616					1.694	0.166

Note: The eleven items excluded for low loading are represented with *.

2.4.3 Assessing the formative measurement model

The formative measurement models were chosen due to the characteristics of the items that make up each construct, and they do not presuppose covariance, for which we are seeking to generate a summative indicator (HENSELER, 2021; HAIR et al., 2022). An example is the “COVID-19 effects” construct, the items for which comprise “our industrial sector”, “our suppliers”, “our competitors”, “our demand” and “our factory” “[…] was/were affected by the COVID-19 outbreak”. Although a correlation between them is possible, we intend to generate an indicator that expresses in general terms how the company and other stakeholders have been affected by the COVID-19 pandemic, hence the choice of a formative model.

Various approaches were used to evaluate the constructs' reliability and validity. First, the internal consistency of items was evaluated. Table 2.3 shows that all constructs had Cronbach's alpha (α), rho_A, and composite reliability (CR) values exceeding the minimum recommended threshold of 0.70 (HAIR et al., 2017a). Second, the convergent validity of the constructs was checked using outer loadings and average variance extracted (AVE) scores.

Table 3 shows that most items met the suggested outer loading criteria (between 0.604 to 0.930) (LIM et al., 2021; BAGOZZI and PHILLIPS, 1991) 11 items with low loading were excluded. The AVE scores illustrated that all the constructs exceeded the suggested 0.50 minimum (FORNELL; LARCKER, 1981) (see Table 2.3). Finally, the heterotrait-monotrait (HTMT) ratio was used to check for discriminant validity (HENSELER et al., 2015). As can be seen in Table 2.4, the constructs' HTMT values were all below the conservative threshold of 0.85 (HAIR et al., 2017a), confirming their discriminant validity. As can be seen in Table 2.5, the constructs' values for the Fornell–Larcker (FL) criterion confirm their convergent validity (FORNELL; LARCKER, 1981).

Table 2.4- Discriminant validity results using heterotrait-monotrait (HTMT) ratio correlation.

Construct	1 - LMP	2 - CEC	3 - FC	4 - CR
1- Lean manufacturing practices (LMP)				
2- COVID-19 effects on companies (CEC)	0.097			
3 – The company’s commitment to developing efforts to face future challenges (SC breakdowns) (FC)	0.664	0.101		
4 - Companies’ responsiveness (CR)	0.491	0.158	0.740	
5 - Performance deterioration (PD)	0.193	0.647	0.414	0.301

Table 2.5 Convergent validity result using the Fornell–Larcker (FL) criterion.

Construct	1 - LMP	2 - CEC	3 - FC	4 - CR	5 - PD
1- Lean manufacturing practices (LMP)	0.750				
2- COVID-19 effects on companies (CEC)	-0.047	0.852			
3 - The company's commitment to developing efforts to face future challenges (SC breakdowns) (FC)	0.589	0.081	0.796		
4 - Companies' responsiveness (CR)	0.440	0.099	0.637	0.742	
5 - Performance deterioration (PD)	-0.128	-0.593	-0.341	-0.264	0.709

2.4.4 Estimating the model and hypotheses testing

Table 6 shows that the VIF values for all constructs ranged between 1.010 and 1.595, suggesting that collinearity is not a problem in the model (BECKER et al., 2015), and indicating that the path coefficients can be assessed with confidence. The significances of the various path coefficients were assessed using a bootstrapping technique with 5,000 sub-samples (STREUKENS; LEROI-WERELDS, 2016) and the results illustrated that the control variables (companies' size, business operation, and lean Six Sigma implemented in the company prior to COVID-19) demonstrated insignificant effects across the model (see Table 6). We included company size and business operation as control variables based on previous research that has shown that the impact of the COVID-19 pandemic may differ depending on the size or sector of the company (MOTA et al., 2022; BEHL et al., 2022; MUHAMMAD et al., 2022). We also considered Lean implementation in the company prior to COVID-19 because of its potential influence on the company's maturity in being responsive during the crisis. Moreover, including these control variables aligns with similar research in the field of operations management (KAZANCOGLU et al., 2022; MARODIN et al., 2018; TORTORELLA et al., 2018b).

H1 was supported, as the COVID-19 outbreak significantly impacts companies' performance deterioration (β=0.573; p<0.001). *H2* was supported (the moderating effect will be better explained in Section 4.6), meaning that companies with maturity in LM practices are more responsive when affected by the COVID-19 outbreak (β=0.149; p=0.021). *H3* was also supported, as companies' responsiveness has an inverse relationship with the deterioration of performance (β=–0.207; p<0.001). This means that the more responsive a company is, the smaller the performance deterioration in the face of adversities. *H4* was supported, as companies' responsiveness positively affects companies' commitment to developing efforts to face future challenges (SC breakdowns) (β=0.553; p<0.001). *H5* was also supported, as LM practices positively affect companies’ commitment to developing efforts to face future challenges and future SC breakdowns (β=0.589; p<0.001).

Following Cohen's (2003) guidelines, the COVID-19 effects on performance deterioration had a large effect size (f^2=0.527). Companies' responsiveness and LM practices had a large effect size (f^2=0.348 and f^2=0.531, respectively) on companies' commitment to developing efforts to face future challenges (SC breakdowns). The inverse relationship between companies' responsiveness and companies' performance deterioration had a small effect size (f^2=0,064). LM practices had a small effect size (f^2=0.041) on the relationship between COVID-19 effects and companies' responsiveness. Predictive relevance was assessed through Stone–Geisser's Q^2 statistic (GEISSER, 1974; STONE, 1974). The Q^2 value for performance deterioration was 0.187, for companies' responsiveness it was 0.234, and for companies' commitment to developing efforts to face future challenges (SC breakdowns) it was 0.216; as all values are greater than zero, the model has predictive relevance. We assessed the structural model through several core metrics to demonstrate model fit. We examined the R-square (R^2) value, effect size (f^2) and predictive relevance (Q^2), and the inner VIF to show the percentage of variance explained, the strength of the relationship between variables, and that the model tested was free of multicollinearity (Table 2.6).

Table 2.6 Results of the structural model testing.

Path Relationship	**Direct Effect**	**Bootstrap Mean**	**Bootstrap SD**	**t-value**	**p-values**	**VIF**	R^2	f^2	Q^2
COVID-19 effects on companies -> Performance deterioration (**H1**)	0.573	0.575	0.051	11.173	0.000	1.010	0.394	0.527	0.187
COVID-19 effects on companies * Lean manufacturing practices -> Companies' responsiveness (**H2**)	0.149	0.124	0.065	2.043	0.021	1.013		0.041	
Companies' responsiveness -> Performance deterioration (**H3**)	-0.207	-0.211	0.062	-3.355	0.000	1.010		0.064	
Companies' responsiveness -> The company's commitment to developing efforts to face future challenges (SC breakdowns) (**H4**)	0.553	0.558	0.076	7.263	0.000	1.584		0.348	
Lean manufacturing practices -> The company's commitment to developing efforts to face future challenges (SC breakdowns) (**H5**)	0.589	0.594	0.059	9.927	0.000	1.595	0.347	0.531	0.216
Control Variables									
Companies Size -> Companies' responsiveness	-0.134	-0.128	0.066	-2.037	0.979	1.165			
Business operations -> Companies' responsiveness	-0.014	-0.011	0.057	-0.243	0.596	1.222			
Lean six sigma implemented in company previous to COVID-19 -> Companies' responsiveness	0.034	0.034	0.061	0.548	0.292	1.089			

The PLSpredict technique (SHMUELI, 2019) was used to examine the prediction relevance of the endogenous construct. As presented in Table 2.7, most of the values for performance deterioration, companies' responsiveness, and companies' commitment to developing efforts to face future challenges (SC breakdowns) and their items had a lower prediction error [i.e., root mean squared error (RMSE) and mean absolute error (MAE)] than the linear model, suggesting that the constructs have a medium prediction power (SHMUELI, 2019).

Table 2.7 - Results of PLSpredict.

	PLS			LM			PLS-PM		
Constructo	**RMSE**	**MAE**	**Previsão_Q²**	**RMSE**	**MAE**	**Previsão_Q²**	**RMSE**	**MAE**	**Previsão_Q²**
Performance deterioration									
Prodaffe	1.849	1.597	0.207	1.937	1.618	0.128	-0.088	-0.021	0.079
Finaperf	1.685	1.439	0.256	1.716	1.407	0.227	-0.031	0.032	0.029
Globperf	1.797	1.504	0.226	1.901	1.529	0.132	-0.104	-0.025	0.094
Capaavai	1.632	1.351	0.209	1.719	1.406	0.124	-0.087	-0.055	0.085
Wastincr	1.541	1.140	0.043	1.580	1.191	-0.004	-0.039	-0.051	0.047
Delaincr	1.882	1.576	0.085	1.953	1.601	0.014	-0.071	-0.025	0.071
leadtime	1.753	1.459	0.130	1.819	1.477	0.065	-0.066	-0.018	0.065
Invedecr	2.132	1.870	0.145	2.297	1.960	0.006	-0.165	-0.090	0.139
The company's commitment to developing efforts to face future challenges (SC breakdowns)									
Adopind4.0	1.543	1.229	0.226	1.583	1.214	0.186	-0.040	0.015	0.040
Buyipatt	1.182	0.923	0.166	1.249	0.964	0.069	-0.067	-0.041	0.097
Flexresp	1.191	0.909	0.214	1.249	0.952	0.136	-0.058	-0.043	0.078
JITSupp	1.383	1.066	0.277	1.466	1.104	0.189	-0.083	-0.038	0.088
Mainprod	1.432	1.108	0.141	1.517	1.182	0.033	-0.085	-0.074	0.108
Companies' responsiveness									
Physdist	1.353	1.074	0.051	1.439	1.149	-0.077	-0.086	-0.075	0.128
Finacons	1.373	1.078	0.090	1.397	1.097	0.058	-0.024	-0.019	0.032
Provheal	1.048	0.752	0.108	1.086	0.796	0.041	-0.038	-0.044	0.067
Workremo	1.795	1.397	0.058	1.916	1.506	-0.072	-0.121	-0.109	0.130
Criscomm	1.798	1.377	0.061	1.841	1.397	0.012	-0.043	-0.020	0.049
Orgaresp	1.204	0.911	0.168	1.238	0.906	0.121	-0.034	0.005	0.047
Digitech	1.802	1.440	0.085	1.916	1.527	-0.040	-0.114	-0.087	0.125

2.4.5 Statistical Robustness checks

To check the robustness of the results, a series of supplementary analyses were undertaken, including nonlinearity, endogeneity, and unobserved heterogeneity (SARSTEDT et al., 2019). We used Ramsey's regression specification error test (RESET) (WOOLDRIDGE, 2020) to detect potential nonlinearities, and a *p*-value >0.05 was found for every possible quadratic relationship in the model. Therefore, we conclude that our model is free from model specification errors (Appendix B).

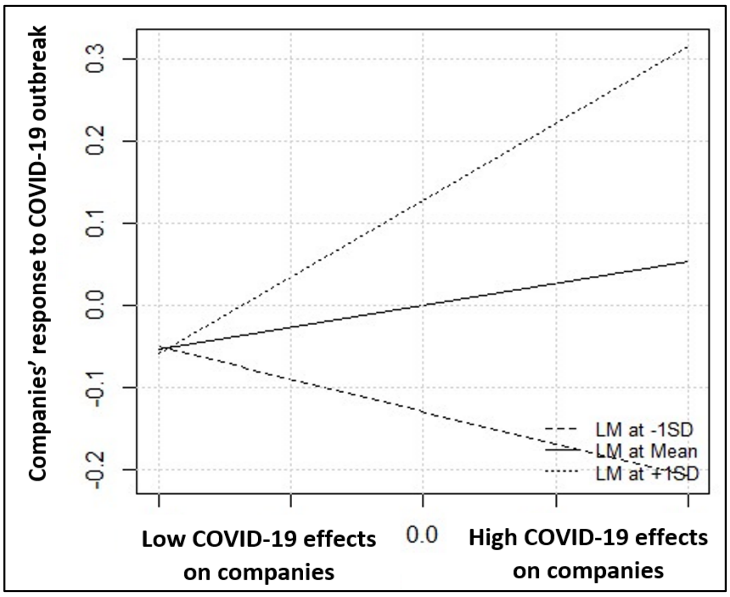
As this study examined several hypotheses, it is crucial to consider potential endogeneity problems that could arise if constructs were omitted (SARSTEDT et al., 2019). We used Park and Gupta's (2012) Gaussian copula approach to examine this issue. The results in Appendix D show the combinations of Gaussian copulas in the model. As none were significant ($p>0.05$), we can conclude there are no endogeneity problems, confirming the model's robustness (HULT et al., 2018).

Finally, potential unobserved heterogeneity was examined using the finite mixture PLS (FIMIX-PLS) procedure (SARSTEDT et al., 2017) (Appendix C). Given the minimum sample size required to reliably estimate the model on each segment (Hair et al., 2017a), we evaluated one- and two-segment solutions. The Akaike information criterion (AIC3) and consistent Akaike information criterion (CAIC) statistics, which work well in FIMIX-PLS contexts (SARSTEDT et al., 2011), did not suggest the same solution. Meanwhile, the entropy values were below the commonly suggested 0.50 threshold, suggesting unobserved heterogeneity was not an issue here (LIM et al., 2021).

2.4.6 Moderating effect

The bootstrapping technique was used to examine the suggested moderation effect (Table 6). The two-stage latent interaction technique (BECKER et al., 2018) suggested that LM practices moderate the proposed relationship between COVID-19 effects and companies' responsiveness (β=0,149; $p<0.05$). Thus, *H2* was supported. Due to the positive moderating effect, the interaction plot in Figure 2.2 illustrates that the relationship between COVID-19 effects and companies' responsiveness is much stronger with a high level of LM practices. A high level of LM practices resulted in greater companies' responsiveness, mainly when COVID-19 effects on companies were high. A low level of LM practices resulted in lower companies' responsiveness, mainly when COVID-19 effects on companies were high. This result suggests that the greater the effect of the COVID-19 outbreak on the company, the more responsive the company should be, with the maturity of lean practices strengthening this relationship. Therefore, the companies in the study were more responsive in the presence of the moderating variable LM practices.

Figure 2.2 - Interaction plot (COVID-19 effects on companies * Lean manufacturing practices → Companies' responsiveness).



2.5 DISCUSSION

To the best of our knowledge, this is the first study that provides empirical evidence about the moderating effect of LM in facing SC breakdowns. Other research related to our research is shown following. Reshad et al (2020) showed that adopting LM could contribute to coping with COVID-19 in health environments. Research carried out by Remko (2020) focused on opportunities to close the gap between SC resilience research and industry practice in the COVID-19 era. The authors argued that LM could improve resilience despite reducing inventory. Therefore, inventory can be managed in times of crisis, and agility can be improved without overstock. Further, Abdallah (2021) developed a simulation, and the findings showed the effectiveness of LM implementation during the COVID-19 pandemic in a real case study performed at an aluminium extrusion factory. Our study differs from previous literature because it goes deeply into this topic, providing robust statistical evidence that LM contributes to manufacturing companies' responses to COVID-19.

Besides, our article is different from the previous literature as we support the *H2* hypothesis and show LM's role in helping companies face the COVID-19 pandemic. Through *H2*, we showed the moderating effect of LM in the relationship between COVID-19 and companies' responsiveness. This means that companies are more responsive when they have previously implemented LM practices. A high level of LM practices resulted in greater responsiveness, mainly when the COVID-19 effects on companies were high. A low level of LM practices resulted in lower responsiveness, mainly when the COVID-19 effects on companies were high. To the best of our knowledge, this is the first study that provides empirical evidence about the role of LM in facing the COVID-19 pandemic. This result has practical implications as it presents LM as an approach that goes beyond an improvement approach. Based on our research, the LM can be applied to improve companies' response to major disruptions. This research could also be a reference for managers to use the studied Lean practices to increase their companies responsiveness to remain resilient in times of crisis.

Although our results could not be found in the literature, some recent research presented results in line with ours. For example Muhammad et al. (2022) developed a survey showing that operational excellence achieved during the COVID-19 pandemic using Lean, Six Sigma, and Sustainability practices in the small-medium enterprise (SME) positively impacts performance. Demirtas et al. (2022) developed a case study and show that Lean tools reduce wastage rates and stoppages, creating a more efficient and sustainable workplace in SME. Tortorella et al. (2022) indicated that Lean Supply Chains (LSC) adapts to keep interactions as linear as possible through transparent information flows and collaborative work while at the same time temporarily reducing tight couplings through inventory increases. Dubey et al. (2023) research show the government's effective role during COVID-19 in enhancing supply chain resilience by enhancing digital adaptability and agility. Bianco et al (2023), using a survey, showed the role of Industry 4.0 to improve companies' responses to the crisis. Behl et al. (2022) develop a survey about big data analytics capabilities to improve the sustainable competitive advantage of SMEs during COVID-19.

Although these closely related research, to the best of our knowledge, this paper is the first to show the role of the LM as a moderator to improve companies' response to the COVID-19 outbreak.

H3, which was also supported, concerns the importance of companies' responsiveness in minimizing performance deterioration in times of crisis. Thus, our results are also confirmed by previous research, such as that of Piprani et al. (2020), who indicated that SC integration contributed significantly to SC resilience, while SC resilience impacted SC performance substantially. Furthermore, to reduce harmful effects on the SC, companies’ instant and effective responses must be developed in relation to the resources (SINGH et al., 2019). So to address the emergent challenges, firms are adopting methods and processes that are proactive and responsive rather than reactive to the crisis (VERMA; GUSTAFSSON, 2020).

The results from supporting hypotheses H2 and H3 can be discussed under the ET lens proposed by Peters and Waterman (1982) and Kessler (2013). The authors show that to be excellent, companies must work hard to keep things simple in a complex world, which is part of Lean philosophy. Our results reinforce the proposition that Lean companies maintain the operational excellence acquired with the maturity of the Lean practice and that companies can be responsive even in times of global disruption. Although operational excellence is well known recognized as a mean to improve company´s performance, our study also showed that operational excellence (acquired through LM) was also essential to sustain the company's responsiveness during COVID-19. This is a novelty contribution to this theory.

H4, which was supported, concerns the positive influence of companies' responsiveness in the commitment to develop efforts to face future SC breakdowns. This result shows that a responsive company can develop efforts to cope with crises and adapt to the challenges that arise after the rupture. This result corroborates Peschl's (2021) research, which proposed a link between organizational learning and future-driven innovation. This author showed that past experiences and already existing knowledge often drive organizational learning and innovation. Our result shows that existing knowledge that makes companies responsive during the COVID-19 outbreak leads to better commitment to developing efforts to face future challenges. Responsiveness is not only about the development of efforts to survive in times of crisis, but also about the efforts that the market may require for survival in a post-pandemic world, to remain competitive, and to be aligned with new business models, sustainability, innovation, and emerging technologies. Our research is aligned with the existing literature on lessons learned from the COVID-19 pandemic, such as Akapan's (2022) study that examines this aspect and evaluates state-of-the-art technologies used by SMEs to enhance operational performance and establish sustainable competitive advantages amid the pandemic.

H5, which was also supported, deals with LM practices positively impacting the company's commitment to developing efforts to face future SC breakdowns. Our results are compatible with other studies in the literature in the SC context (BRYCE et al., 2020; FONSECA; AZEVEDO, 2020). These authors stated that lean, to a certain extent, contributes to the future preparation of companies concerning the COVID-19 pandemic. However, lean needs to be reinvented to do this, mainly regarding stock positioning in the SC.

Craighead et al. (2020) argued that longstanding ideas of what is and is not legitimate during the pandemic are being ignored as companies desperately respond to extreme shifts in supply and demand. The authors cited LM as an example. During the COVID-19 pandemic, although LM is a consecrated philosophy and has been widely adopted since the 1980s, it was questioned amid rampant stockouts. These authors argued that, due to the dramatic changes that accompany a pandemic, new conceptions of legitimate and successful behaviour are expected to emerge afterward, resulting in some permanent transformations in SC processes. Further, in a post-COVID-19 organizational environment, time-honoured traditions such as LM will rise or fall on their own merits rather than being assumed to be legitimate. Therefore, studies about future challenges and the post-pandemic evolution of other mainstream SC strategies would be a fruitful path to pursue.

The results from supporting hypotheses H4 and H5 are discussed under the RT lens proposed by Kessler (2013). The author points out that RT is a learning theory, so relatively permanent behavior change is achieved through reinforced practice or experience. Our results confirm that both the maturity of Lean practices and the responsiveness improve the commitment of companies to develop efforts to face future challenges in the post-COVID-19 world or future crises. Our research novelty contribution to RT is to show that Lean companies and responsiveness companies have a more positive work environment that is conducive to reinforcement and learning.

2.6 CONCLUSIONS

2.6.1 Academic novelty and contributions

The LM literature has proven the efficacy of this management approach for improving organizational performance in several sectors. However, during the COVID-19 pandemic, some authors criticized LM, reporting the need for adaptations concerning low levels of stock in times of pandemic (BRYCE et al., 2020; FONSECA; AZEVEDO, 2020). Our position about this discussion is that the LM played an important role in facing COVID-19. So the operational excellence achieved through LM practices is not lost in times of crisis. In this way, companies with maturity in LM were more responsive during the COVID-19 pandemic. This research contributes to the literature presenting the role of LM in moderating the relationship between COVID-19's negative effects and companies' responses. Our study showed thatLean companies are committed to developing efforts to face the challenges in a post-COVID-19 world.

Concerning the theory of operations management, our results contribute as follows. In light of the ET of Kessler (2013), first, we showed that LM practices can moderate the COVID-19 effects on companies' responsiveness. Second, we showed that operational excellence is one way to be responsive in major breakdowns. In this research, the ET was considered when verifying that the operational excellence achieved by LM is not lost in times of crisis. In light of the RT of Kessler (2013), first, we showed that responsive companies are more committed to the efforts to face future challenges and breakdowns. Second, showed that LM is a means for companies to acquire positive behaviour toward future actions facing challenges.

Our results show that the greater the maturity of companies' lean practices, the more responsive companies will be in the face of the COVID-19 pandemic. Studies addressing LM and the COVID-19 outbreak in operations management are still scarce. However, studies before the COVID-19 pandemic have demonstrated that LM improves important aspects in facing major breakdowns, reinforcing our results. An example is Lotfi and Saghiri (2018), who conducted a survey in which the findings showed that lean operations positively affect the cost, delivery, and flexibility performance, leading to a better time to recovery performance. Benítez et al. (2018) developed a model that revealed that lean SC practices act as drivers for resilient SC practices, and that lean SC practices lead to a more significant performance improvement.

Another main theoretical contribution of our study is statistically proving the role of LM in helping manufacturing industries overcome the effects of the COVID-19 outbreak on operations. Further, the present study contributes to the literature by showing that LM practices and companies' responsiveness influence the committed to development of efforts to face future challenges, in light of the RT of Kessler (2013). In this research, RT was considered when evaluating whether past experiences and already existing knowledge drive organizational learning and innovation. Nandi et al. (2021) argued that one crucial aspect of operations theory is related to continuous improvement. In a post-COVID-19 world, the focus of continuous improvement could shift to change and agility rather than price, cost, and leanness. Aiming to study this issue as a future challenge for LM, JIT supply (JITSupp) was considered a variable manifested in the COVID-19 future challenges construct. Thus, it can be confirmed that adopting LM still proves to be a means to obtain a favorable outcome from the point of view of the competitiveness of companies in being committed to developing efforts to face future challenges arising from a pandemic.

To the best of our knowledge, this is the first empirical research that presents the role of LM in operations management during the COVID-19 pandemic. As pointed out by previous research, studying the post-pandemic evolution of other mainstream SC strategies (e.g. global sourcing) would be a fruitful path to pursue. Table 8 summarizes the main academic contributions of our research.

2.6.2 Management contributions

Regarding managerial implications, this study presents LM for companies as a philosophy that goes beyond continuous improvement and, if well implemented, provides companies with the tools necessary to overcome future crises and disruptions, promoting responsiveness. Our research provides a guideline to managers committed to resilience when showing the LM practices that are correlated with responsiveness. Besides the results suggest that lean helped companies to face COVID-19 outbreak more efficiently, once it has an organizational culture open to changes and innovations. Therefore, our research proves that long-term investments in practices and tools for continuous improvement bring benefits not only to the companies' routine but also in times of crisis and post-disruption recovery. Thus, managers can adopt the Lean approach, focusing on results that go beyond waste reduction. Table 8 summarizes the main managerial contributions of our research.

This article has sought to provide a sustainable perspective regarding COVID-19 future challenges that companies will be facing. Therefore, managers need to be aware of companies' positions in the SC to avoid disruption, downstream and/or upstream of their company, which would compromise business performance. Furthermore, the current study also shows that organizations must invest in lean practices to understand the “new normal” when considering JIT sourcing practices targeting the unit lot, so that there is no saturation of such a lean practice, but rather an improvement of it. Therefore, as already explored in the LM literature, managers must be cautious regarding the financial returns of initial investments in LM adoption, materialized in business performance, especially in an adaptation period due to the pandemic.

Based on the findings of our study could be suggested an action plan for engineering/operations managers prepare the companies to be robust in times of crisis:

1. First, ensuring that the LM has been correctly applied in the company is necessary. Managers must ensure that production has been responsive and that the policy of reducing inventory and lot size has actually reduced the lead time. Once production pull flow is efficient, in times of crisis with high demand variability, it will be possible to respond quickly to the customer's request. This prevents high inventories, which is a problem in times of crises with low demand. In addition, production in a small lot allows flexibility, and managers could adapt the production plan to focus on products in most significant demand (LOPES et al., 2023).
2. Second, it is necessary to ensure that the company formalizes partnerships and establishes a good feedback relationship with suppliers. According to our findings, the spread of LM through the SC is a critical practice to be robust in times of crisis. So, managers that establish communication and partnership with suppliers obtain information in advance about the lack of some supply and could be a priority in supply due to partnership.
3. Third, managers must ensure that the companies' employees understand and utilizes LM as a philosophy. The post-lockdown period required greater discipline from

employees to follow health and safety rules. When Lean is part of the company´s culture, employees are already used to following standards and procedures; so, adapting to new rules imposed during the pandemic periods is easier. In addition, the culture of experimentation and risk-taking is part of Lean companies, so they are committee to the development of efforts to face the challenges in a post-COVID-19 world.

Table 2.8 - Academic novelty and contributions of the present research

Main results	Contribution to LM literature	Contribution to theory	Managerial implication
The level of LM implementation in companies moderates the relationship between the COVID-19 effects and companies' responsiveness.	Our research is the first to present LM practices as a moderating variable that enhances responsiveness concerning the COVID-19 effects on companies.	Our research contributes to the evolution of the ET because the results suggest that operational excellence is not lost even in times of unprecedented crisis.	Our research contributes to managers when showing how companies could take advantage of Lean practices even in times of crisis.
Responsiveness in Lean companies enables performance stability in times of crisis.	This finding contributes to the evolution of LM theory by addressing the approach as a means of achieving responsiveness. The literature that addresses the relationship between LM and responsiveness is still scarce.	Our research contributes to the evolution of the ET because the results suggest that operational excellence is one way to be responsive in major breakdowns.	Our research provides a guideline to managers committed to resilience when showing the LM practices that are correlated with responsiveness.
Responsive companies are more committed to efforts to face the challenges in a post-COVID-19 world and future breakdowns.	This finding contributes to the evolution of LM when showing evidence that operational responsiveness is an important aspect of Lean companies. This combination strengthens companies to face the challenges in the post-COVID-19 world.	Our research contributes to the evolution of the RT, once it shows that responsive companies are more committed to the efforts to face future challenges and breakdowns. So, good results concerning responsiveness lead to more compromise concerning measures to be taken to face future challenges.	Companies that are unable to maintain performance during the COVID-19 pandemic can find in our research some solutions to better respond to future breakdowns.
The level of LM in the company influences the commitment to efforts to face future challenges (SC breakdowns).	This finding contributes to the LM literature because it shows that companies with Lean culture could adapt to the innovations and challenges that the post-COVID-19 world will require.	Our research contributes to the RT once it shows that Lean companies have a more positive work environment that is conducive to reinforcement and learning. So, our result shows that LM is a mean for companies to acquire a positive behaviour towards future actions facing major breakdowns.	Based on our result, managers could understand LM not only as an improvement approach but also as an approach aligned with resilience and openness to innovation. Thus, managers can adopt the Lean approach, focusing on results that go beyond waste reduction.

2.6.3 Study limitations and opportunities for new research

Given the concerns regarding, and definition of boundary conditions for the development of this research, certain limitations are inherent to this study. First, there is a lack of data collection from other countries to compare different scenarios and our data is based on respondents' perceptions and confident data that they have access Therefore, expanding data collection considering manufacturing companies from other countries would allow diversification in data analysis and complementary insights. Another limitation is the lack of longitudinal data, which is extremely important to assess the implications of the COVID-19 pandemic, which are momentary, on companies' performance and even on managing manufacturing operations. In other words, observing the long-term implications is a necessary and pertinent assessment. A third limitation is related to the assessment of LM as a means to maintain organizational performance in times of crisis. This represents an opportunity for future research, since manufacturing companies can use other systems for continuous improvement in production management, such as Six Sigma, Industry 4.0, or even other agile approaches. Moreover, we encourage the development of in-depth case studies that address companies' measures to address the COVID-19 outbreak that may allow a better understanding of how companies should act in a post-COVID-19 world, and how to tackle future pandemics or disruptive events. For future research, studies that address econometric data to measure the COVID-19 effects and the operational performance of companies would be an important contribution to the literature.

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APPENDIX A. RESEARCH QUESTIONNAIRE

1. Please, answer the following information with respect to the company you work for:
(a) Does your company have Lean initiatives implemented? (b) How long has your company been implementing Lean philosophy? (c) Your job title within your company: (d) How long do you have experience?: __________years (e) Type of organization: ( ) Multinational ( ) Single country (f) Size of the organization: ( ) 1 – 10 Employees ( ) 11 – 50 Employees ( ) 50 – 100 Employees ( ) More than 100 Employees (g) Markets attended by the company: (h) Brazilian state of the organization:

2. Please, about the Lean Practices adopted in the company, indicate your level of agreement. * *Scale: from 1 (fully disagree) to 7 (fully agree)*(Lean manufacturing practices implemented before COVID-19)
(a) The organization establishes a good feedback relationship with its suppliers.
(b) The organization formalizes partnerships with its suppliers. They can get involved in the development of new products, in the production and delivery process.
(c) The organization promotes the development of its suppliers. They can be more involved in the production and delivery process.
(d) The organization focuses on its customers and their needs.
(e) The organization uses Just-in-time (JIT) production with Kanban of signals for production.
(f) The organization establishes mechanisms that allow and facilitate the continuous flow of products.
(g) The organization is working to lower setup times in the plant.
(h) The organization guarantees a low defect rate for products in the process.
(i) The organization's employees have a role in problem-solving and functional teams.
(j) The organization addresses equipment downtime using total productive maintenance to achieve a high level of equipment availability.
(k) The organization uses improvement experts who are developed through certification programs and who have specific leadership roles and responsibilities in improvement teams.
(l) The organization follows a standardized procedure in planning and carrying out improvement projects and uses appropriate Quality Management tools and techniques, as prescribed in each step of the structured procedure. ( )
(m) The organization applies lean principles in office operations.

3. Please, considering the impacts of the COVID-19 pandemic on your organization, please indicate below your level of agreement with the following statements: * *Scale: from 1 (fully disagree) to 7 (fully agree)* (COVID-19 effects)
(a) Our industrial sector was strongly affected by the COVID-19 pandemic.
(b) Our company was strongly affected by the COVID-19 pandemic.
(c) Our suppliers were strongly affected by the COVID-19 pandemic.
(d) Our competitors were strongly affected by the COVID-19 pandemic.
(e) Our demand was strongly affected by the COVID-19 pandemic.

4. Considering measures taken by your company in response to the crisis caused by the COVID-19 outbreak, please, indicate your level of agreement: * *Scale: from 1 (fully disagree) to 7 (fully agree)* (Companies' responsiveness)
(a) We managed to deal with the sudden disruption of suppliers
(b) We have not had any significant delays in delivering our products
(c) We managed to deal with the sudden change in demand for our products
(d) We were able to provide health, safety, and hygiene to our employees and customers
(e) We were able to remotely working when it was required

(f) We had no capacity restrictions on the production
(g) We can deal with physical distribution problems caused by the COVID-19 pandemic
(h) We were able to deal with financial constraints caused by the COVID-19 pandemic
(i) Our company created a crisis management committee to deal with the effects of COVID-19
(j) Our organization has been responsive and flexible during the COVID-19 pandemic
aspects due to limited resources and access
(k) Our organization employed digital technologies in its operations to overcome COVID-19 pandemic challenges
(l) Our policy of continually seeking to reduce waste has helped us to overcome the challenges of the pandemic
(m) Our organization has a risk management system in the supply chain as a way to mitigate the effects of COVID-19 pandemic

5. Considering the challenges that the COVID-19 pandemic will bring to your organization/supply chain, please indicate below your level of agreement with the following statements: ** Scale: from 1 (fully disagree) to 7 (fully agree)* (The company's commitment to developing efforts to face future challenges /SC breakdowns).
(a) Our organization will promote efforts to adopt technologies from Industry 4.0 to adapt/expand our business ( )
(b) Our organization will promote efforts to develop resilience and preparation for future similar events
(c) Our organization will promote efforts to develop safe health and hygiene conditions for workers in the context of COVID-19
(d) Our organization will promote efforts to identify behavior changes in customers' purchasing patterns in the post-COVID world
(e) Our company will promote efforts to develop flexibility and responsiveness in our supply chain to address future reductions in workforce and capacity
(f) Our organization will promote efforts to flexible the concept of "just in time" supply to prevent a shortage of supplies in disruption and crises times
(g) Our organization will promote efforts to maintain productivity even with a possible reduction in working days during the year

6. Please, regarding the company's performance since March 2020, you could indicate your level of the agreement on the following: ** Scale: from 1 (fully disagree) to 7 (fully agree)* (Performance deterioration)
(a) Productivity in our company has been affected negatively by the COVID -19 pandemic
(b) The quality of our product has been negatively affected by the COVID-19 pandemic
(c) Waste in our company increased in the period mentioned
(d) Our company's financial performance has been affected negatively by the COVID-19 pandemic
(e) The overall performance of our company has been affected directly by the economy's "open/close"
(f) The defect rate of our products increased during the COVID-19 pandemic
(g) The delay in delivering our orders increased during the COVID-19 pandemic
(h) We had raw materials' shortage during the COVID-19 pandemic
(i) Finished product inventory levels decreased during the COVID-19 pandemic
(j) The time elapsed from the customer's order until the customer received it (lead time) worsened during the COVID-19 pandemic
(k) Our company's capacity availability was negatively affected by the COVID-19 pandemic

APPENDIX B. ASSESSMENT OF NONLINEAR EFFECTS

Nonlinear relationship	Coefficient	p-value	Ramsey's RESET
Lean manufacturing practices * Lean manufacturing practices -> The company's commitment to developing efforts to face future challenges (SC breakdowns)	0.053	0.141	F (1.2709). p-value = 0.2828
Companies' responsiveness * Companies' responsiveness -> The company's commitment to developing efforts to face future challenges (SC breakdowns)	0.016	0.627	
COVID-19 effects on companies * COVID-19 effects on companies -> Companies' responsiveness	0.056	0.349	F (1.1166). p-value = 0.3499
Lean manufacturing practices * Lean manufacturing practices -> Companies' responsiveness	0.087	0.057	
COVID-19 effects on companies * COVID-19 effects on companies -> Performance deterioration	0.033	0.527	F (0.1522). p-value = 0.9618
Companies' responsiveness * Companies' responsiveness -> Performance deterioration	-0.001	0.980	

APPENDIX C. RESULTS OF THE UNOBSERVED HETEROGENEITY TEST USING THE FIMIX-PLS APPROACH

Criteria	Number of Segments	
	1	2
AIC (Akaike's Information Criterion)	1435.94	1403.003
AIC3 (Modified AIC with Factor 3)	1445.94	1424.003
AIC4 (Modified AIC with Factor 4)	1455.94	1445.003
BIC (Bayesian Information Criteria)	1469.023	1472.477
CAIC (Consistent AIC)	1479.023	1493.477
HQ (Hannan Quinn Criterion)	1449.325	1431.112
MDL5 (Minimum Description Length with Factor 5)	1681.353	1918.371
LnL (LogLikelihood)	-707.97	-680.502
EN Entropy Statistic (Normed))		0.375
NFI (Non-Fuzzy Index)		0.439
NEC (Normalized Entropy Criterion)		126.215

APPENDIX D. RESULTS OF THE ENDOGENEITY TEST USING THE GAUSSIAN COPULA APPROACH

Test	Construct	Coefficient	SE	t-value	p-value	bootBias	bootSE	bootMed	p-value
Gaussian copula of model 1	COVID-19 effects on companies	0.293	0.196	1.491	0.138	0.024	0.366	0.287	0.425
Endogenous variables: COVID-19 effects on companies	Lean manufacturing practices	0.430	0.064	6.674	0.000	-0.007	0.072	0.424	0.000
Exogenous variable: Companies' responsiveness	COVID-19 effects on companies * Lean manufacturing practices	0.090	0.064	1.410	0.160	-0.013	0.082	0.078	0.275
	COVID-19 effects on companies c	-0.174	0.182	-0.955	0.341	-0.023	0.386	-0.163	0.654
Gaussian copula of model 2	COVID-19 effects on companies	0.115	0.063	1.835	0.068	0.007	0.069	0.123	0.098
Endogenous variables: Lean manufacturing practices	Lean manufacturing practices	0.438	0.108	4.064	0.000	-0.013	0.125	0.427	0.001
Exogenous variable: Companies' responsiveness	COVID-19 effects on companies * Lean manufacturing practices	0.117	0.057	2.046	0.042	-0.015	0.092	0.110	0.202
	Lean manufacturing practices c	0.005	0.067	0.082	0.935	0.003	0.049	0.009	0.911
Gaussian copula of model 3	COVID-19 effects on companies	0.125	0.062	1.997	0.047	0.008	0.067	0.132	0.063
Endogenous variables: COVID-19 effects on companies * Lean manufacturing practices	Lean manufacturing practices	0.407	0.065	6.255	0.000	-0.003	0.070	0.405	0.000
Exogenous variable: Companies' responsiveness	COVID-19 effects on companies * Lean manufacturing practices	0.385	0.151	2.553	0.011	-0.152	0.328	0.364	0.241
	COVID-19 effects on companies * Lean manufacturing practices c	-0.308	0.160	-1.919	0.057	0.136	0.298	-0.273	0.302
Gaussian copula of model 4	COVID-19 effects on companies	0.298	0.198	1.502	0.135	0.024	0.367	0.290	0.418
Endogenous variables: COVID-19 effects on companies and Lean manufacturing practices	Lean manufacturing practices	0.411	0.111	3.703	0.000	-0.016	0.118	0.397	0.001
Exogenous variable: Companies' responsiveness	COVID-19 effects on companies * Lean manufacturing practices	0.090	0.064	1.413	0.159	-0.013	0.082	0.079	0.274
	COVID-19 effects on companies c	-0.179	0.184	-0.971	0.333	-0.023	0.387	-0.166	0.645
	Lean manufacturing practices c	0.014	0.067	0.207	0.836	0.005	0.047	0.018	0.767
Gaussian copula of model 5	COVID-19 effects on companies	0.155	0.212	0.732	0.465	0.054	0.391	0.179	0.692
Endogenous variables: COVID-19 effects on companies and COVID-19 effects on companies * Lean manufacturing practices	Lean manufacturing practices	0.406	0.066	6.178	0.000	0.000	0.068	0.406	0.000

Test	Construct	Coefficient	SE	t-value	p-value	bootBias	bootSE	bootMed	p-value
Exogenous variable: Companies' responsiveness	COVID-19 effects on companies * Lean manufacturing practices	0.371	0.180	2.055	0.041	-0.149	0.336	0.300	0.271
	COVID-19 effects on companies c	-0.030	0.201	-0.151	0.880	-0.052	0.411	-0.043	0.941
	COVID-19 effects on companies * Lean manufacturing practices c	-0.296	0.178	-1.663	0.098	0.136	0.301	-0.221	0.326
Gaussian copula of model 6	COVID-19 effects on companies	0.126	0.063	2.021	0.045	0.009	0.067	0.135	0.062
Endogenous variables: Lean manufacturing practices and COVID-19 effects on companies * Lean manufacturing practices	Lean manufacturing practices	0.357	0.114	3.120	0.002	0.006	0.118	0.363	0.003
Exogenous variable: Companies' responsiveness	COVID-19 effects on companies * Lean manufacturing practices	0.406	0.156	2.602	0.010	-0.155	0.338	0.385	0.231
	Lean manufacturing practices c	0.037	0.068	0.537	0.592	-0.004	0.048	0.031	0.450
	COVID-19 effects on companies * Lean manufacturing practices c	-0.308	0.160	-1.919	0.057	0.139	0.307	-0.289	0.286
Gaussian copula of model 7	COVID-19 effects on companies	0.161	0.213	0.757	0.450	0.068	0.391	0.198	0.681
Endogenous variables: Lean manufacturing practices	COVID-19 effects on companies * Lean manufacturing practices	0.355	0.115	3.082	0.002	0.005	0.115	0.361	0.002
Exogenous variable: Companies' responsiveness	COVID-19 effects on companies * Lean manufacturing practices	0.390	0.184	2.117	0.036	-0.148	0.335	0.315	0.246
	COVID-19 effects on companies c	-0.034	0.201	-0.170	0.865	-0.065	0.411	-0.063	0.934
	Lean manufacturing practices c	0.037	0.068	0.541	0.589	-0.004	0.047	0.033	0.434
	COVID-19 effects on companies * Lean manufacturing practices c	-0.315	0.182	-1.734	0.085	0.137	0.301	-0.240	0.297
Gaussian copula of model 8	Companies' responsiveness	0.414	0.073	5.655	0.000	-0.002	0.077	0.413	0.000
Endogenous variables: Companies' responsiveness	Lean manufacturing practices	0.382	0.054	7.035	0.000	0.000	0.062	0.383	0.000
Exogenous variable: Companies' commitment to developing efforts to face future challenges in a post-COVID word	Companies' responsiveness c	0.040	0.036	1.100	0.273	0.001	0.028	0.041	0.161
Gaussian copula of model 9	Companies' responsiveness	0.468	0.054	8.601	0.000	-0.003	0.060	0.466	0.000
Endogenous variables: Lean manufacturing practices	Lean manufacturing practices	0.375	0.087	4.285	0.000	0.002	0.097	0.377	0.000
Exogenous variable: Companies' commitment to developing efforts to	Lean manufacturing practices c	0.006	0.052	0.122	0.903	0.000	0.062	0.010	0.919

Test	Construct	Coefficient	SE	t-value	p-value	bootBias	bootSE	bootMed	p-value
face future challenges in a post-COVID word									
Gaussian copula of model 10	Companies’ responsiveness	0.414	0.074	5.581	0.000	-0.002	0.080	0.413	0.000
Exogenous variables: Companies’ responsiveness and Lean manufacturing practices	Lean manufacturing practices	0.387	0.088	4.393	0.000	-0.001	0.098	0.387	0.000
Exogenous variable: Companies’ commitment to developing efforts to face future challenges in a post-COVID word	Companies’ responsiveness c	0.040	0.037	1.093	0.276	0.000	0.031	0.040	0.193
	Lean manufacturing practices c	-0.004	0.053	-0.076	0.940	0.001	0.064	-0.001	0.950
Gaussian copula of model 11	COVID-19 effects on companies	0.422	0.157	2.687	0.008	-0.002	0.202	0.427	0.038
Endogenous variables: COVID-19 effects on companies	Companies’ responsiveness	0.219	0.057	3.870	0.000	0.008	0.058	0.227	0.000
Depende variable: Short term companies performance	COVID-19 effects on companies c	0.147	0.143	1.026	0.306	0.000	0.197	0.140	0.457
Gaussian copula of model 12	COVID-19 effects on companies	0.562	0.056	10.046	0.000	-0.003	0.059	0.559	0.000
Endogenous variables: Companies’ responsiveness	Companies’ responsiveness	-0.144	0.079	1.830	0.069	-0.002	0.085	-0.145	0.093
Depende variable: Short term companies performance	Companies’ responsiveness c	-0.047	0.041	1.131	0.259	-0.000	0.040	-0.048	0.245
Gaussian copula of model 13	COVID-19 effects on companies	0.428	0.157	2.724	0.007	0.002	0.197	0.430	0.031
Endogenous variables: COVID-19 effects on companies and Companies’ responsiveness	Companies’ responsiveness	-0.160	0.080	1.984	0.049	-0.008	0.084	-0.169	0.060
Depende variable: Short term companies performance	COVID-19 effects on companies c	0.132	0.144	0.917	0.360	-0.004	0.193	0.125	0.495
	Companies’ responsiveness c	-0.043	0.041	1.033	0.303	0.002	0.039	-0.043	0.280

Note: Shapiro-Wilk normality test on the latent variable scores [i.e.. COVID-19 effects on companies (p-value = 0.0001). Performance deterioration (p-value = 0.0000). Companies’ responsiveness (p-value = 0.0000)] were significant. allowing us to proceed with Park and Gupta's (2012).

CHAPTER 3 THE ROLE OF INDUSTRY 4.0 IN DEVELOPING RESILIENCE FOR MANUFACTURING COMPANIES DURING COVID-19

In this chapter, the second thesis paper will be presented. This paper is a survey about the role of Industry 4.0 in helping organizations to face the COVID-19 outbreak. This paper has already been published in the journal "International Journal of Production Economics" (DOI: https://doi.org/10.1016/j.ijpe.2022.108728).

Abstract: Humanity has faced many crises in the past, such as pandemics, wars, and economic crises, and other crises are certain to come in the future; however, emerging technologies have a role to play in improving companies' resilience in the face of such crises. The coronavirus (COVID-19) pandemic has led to human, technological, and managerial constraints for manufacturing companies due to scarce resources or supply chain (SC) disruptions. The research goal of this paper is to investigate whether Industry 4.0 implementation improved companies' resilience and whether companies' performance maintained stability during the COVID-19 outbreak. Composite-based structural equation modeling is applied to analyse data collected from 207 manufacturing companies. The theoretical model is grounded in the Practice-Based View (PBV) theory. The research findings show that operational responses based on Industry 4.0, smart manufacturing practices, and smart capabilities enable manufacturers to build resilience and quickly mitigate performance loss in times of global crisis. Therefore, the results demonstrate that Industry 4.0 implementation provides resilience for companies through flexibility, reliability, robustness, and responsiveness. The main practical implication of this study is to support managers in achieving manufacturing performance stability during disrupted times, such as the COVID-19 crisis, using Industry 4.0 approaches to make their companies more resilient and prepared to face future challenges and crises.

Keywords: Industry 4.0, Manufacturing performance, Resilience, COVID-19.

3.1 INTRODUCTION

3.1.1 Contextualization and research goals

Major crises have come in many forms over the last quarter-century, including natural disasters, war, insect invasion, terrorism, electoral violence, disease, and economic collapse. Some crises have been confined within regional borders, while others have destabilized the entire world, including global supply chains (SC). Some have made headlines worldwide and drawn immense funding, while others have not garnered international interest. Some have killed thousands of people instantly, while others have slowly affected society over generations.

Examples of crises around the world include the acquired immunodeficiency syndrome (AIDS) epidemic in Africa in the 1990s, the 11 September 2001 terrorist attacks, the Indian Ocean tsunami (2004), Ebola hitting West Africa (2013), the coronavirus (COVID-19) pandemic (2020), and the Russian invasion of Ukraine (2022). Other crises of varying magnitudes are sure to occur in the future, such as ongoing climate change (*The New Humanitarian*, 2022). A common factor in such crises is their influence on the evolution of factors such as humanitarian efforts, technology development, companies' resilience, and business operational and financial performance. The impacts of such crises on companies shape the future of operations management, as practices that have been shown to work well in the past are replicated to deal with future disruption. One possible path that companies can follow is to take advantage of new technologies, such as those that come under the umbrella of "Industry 4.0", in order to remain robust in times of crisis.

The emergence of the novel coronavirus (COVID-19) caused a pandemic that significantly impacted people's lives and health, producing a global economic crisis (World Health Organization WHO, 2023), so it can be considered a relevant contemporary context to study organizational behavior in times of crisis. Several public actions were adopted to limit the pandemic's spread, such as closing countries' borders, restricting commercial activities, and shortening industries' workdays. These actions had several effects on companies' operations and supply chains. The main effects were logistical difficulties for transporting products or inputs/raw materials, difficulties in obtaining the inputs/raw materials used in companies' operations, the need to continue paying for current expenses with reduced revenues, and decreased production (National Confederation of Industry CNI, 2020).

Several mitigation actions were adopted in the manufacturing industry to reduce the effects of COVID-19 (IBN-MOHAMMED et al., 2021). Examples of actions undertaken include reduction of production activity, demobilizing of workers (LAING, 2020), adoption of remote working (RIO-CHANONA et al., 2020), re-distribution of work shifts (International Labour Organization ILO, 2020), adoption of governmental programs to preserve jobs (KUMAR et al., 2020), workstation re-design (SHEN et al., 2020), and adoption of digital technologies (DONTHU; GUSTAFSSON, 2020). Some of these mitigation actions were only possible due to existing digital transformation processes that companies have been adopting in recent years based on Industry 4.0 (I4.0) technologies. I4.0 allows for the creation of cyber-physical systems that connect the physical manufacturing environment with the virtual and remote world through the Internet of Things (IoT), connectivity, and digital systems (FRANK et al., 2019; MEINDL et al., 2021).

Recent studies have suggested that manufacturing companies adopting I4.0 have been better able to deal with the effects of the COVID-19 pandemic (e.g. HOPKINS, 2021; NARAYANAMURTHY; TORTORELLA, 2021; PAPADOPOULOS et al., 2020; SHEN et al., 2020; SPIESKE; BIRKEL, 2021). For example, 'big data' analytics is particularly suitable for improving supply chain resilience through predictive practices and capabilities. Artificial intelligence (AI) solutions enable simulations, which is an essential feature since the occurrence of infections during a pandemic is highly dynamic, requiring regular re-evaluations of supply chain measures (SPIESKE; BIRKEL, 2021). 3D printing has been used to develop face masks (AKPAN et al., 2020), while IoT and blockchain applications can potentially disrupt companies' operations and lead to significant operational improvements during a crisis such as COVID-19 (ALMEIDA et al., 2020).

It is expected that I4.0 technologies can help companies to better cope with this "new normal" in manufacturing operations. However, managers and practitioners still do not know to what extent these initiatives can support companies in reducing the negative effects of the pandemic and how I4.0 resources and technologies can help create an agile manufacturing response to the COVID-19 pandemic and its propagation effects over time. Recent studies have demonstrated the contribution of I4.0 in the COVID-19 context (e.g. HOPKINS, 2021; SHEN et al., 2020 SPIESKE; BIRKEL, 2021). However, these studies have addressed only the general contributions of I4.0 technologies, without extending their research to the specific practices and capabilities created in smart manufacturing environments. This research investigates this gap, since the COVID-19 pandemic required new habits and routines among workers and their operational activities and practices (MEINDL et al., 2021). Accordingly, this study understands that I4.0 programs should go deeper than just implementing technologies, rather using them to perform a critical role in resilience building to mitigate the effects of deteriorating performance during a crisis such as COVID-19. Based on the above discussion, the following research question (RQ) arises: *Is the performance of manufacturing companies less impacted by the COVID-19 crisis when I4.0 is implemented?*

This research investigates the effects of I4.0 implementation on manufacturing performance stability via smart manufacturing, which mediates the development of smart capabilities, using the Practice-Based View (PBV) theoretical lens. The PBV, proposed by Bromiley and Rau (2016), offers operations management research an approach that explains the variation in companies' performance by adopting a set of imitable practices (e.g. practices derived from I4.0 implementation). These practices represent a defined activity or set of activities that various companies should execute to achieve the desired performance

(BROMILEY; RAU, 2014). There is no need for exclusivity in a company adopting these practices to achieve operational improvement; practices are exchangeable within the industry (UMAR et al., 2022a). As a result, several organizations can adopt similar practices, and all will experience performance improvement (UMAR et al., 2022b).

According to Battesini et al. (2021), performance measurement is assessed based on operational and financial measures. The most well-known and commonly used operational performance measures are capacity, productivity, lead time, inventory, and efficiency. These measures are derived from competitive priorities: quality, speed, flexibility, reliability, and cost. Concerning financial measures, the most commonly used financial measures are net profit, return on investment, and cash flow. Besides, the company’s sustainable performance is addressed under the social, environmental, and economic dimensions, regarding the people, the planet, and profit, respectively (BATTESINI et al. 2021; RAJESH, 2022; SLACK et al., 2016). The present research aims to investigate the role of I4.0 implementation in building resilience concerning companies' operational and financial measures. Therefore, our construct "manufacturing companies' performance" in this study considered only operational and financial performance measures. The environmental and social dimensions are beyond this project’s scope and should be considered in future research.

Therefore, the main goal of this research is to investigate whether implementing I4.0 provides a path to resilience building to maintain the stability of manufacturing companies’ performance, even during the COVID-19 crisis. This study uses a survey deployed during the height of the crisis to investigate this matter. Similar to the COVID-19 pandemic, other crises and pandemics may arise and spread in the future. The intent is to demonstrate an alternative strategy for manufacturing managers to meet their organizational performance goals, even in times of disruption to global supply chains.

To achieve the research goal, a survey was conducted with 207 manufacturing companies operating in Brazil during the COVID-19 pandemic. Composite-based structural equation modeling was used to analyse the collected data.

3.1.2 Research gaps

The present study proposes a structural model with 5 hypotheses to address three research gaps (Fig. 1). The model is based on PBV theory, the analysis of recent and established articles in the relevant literature, and expert validation. A systematic literature review (SLR) was carried out to construct the model and the research instrument. Table 3.1 presents the main contributions to the literature that led to identifying these research gaps.

Table 3.1 – Relevant literature in identifying research gaps

Authors	**Main contribution in relation to research gaps**	**Research gap**	**How the present study contributes to addressing this research gap**
Dalenogare et al. (2018)	The authors propose a framework presenting I4.0 technologies and their expected benefits. Additionally, the authors apply a survey in Brazilian industries and discuss the perception of I4.0 technologies in emerging countries.	Research Gap 1: Test previous research theories about I4.0 approaches	This research empirically tests the Industry 4.0 structure proposed in the previous literature. The findings suggest that the industry 4.0 structure is valid, thus corroborating the prior literature.
Kusiak et al. (2018)	The authors present six pillars of smart manufacturing that were important to developing the I4.0 concept in our research.		
Frank et al. (2019)	The authors propose a conceptual framework for I4.0 technologies, which they divide into front-end and base technologies. The authors propose an I4.0 structure that inspired the model proposed in our research.		
Bueno et al. (2020)	The authors conduct an SLR to develop an analytical framework that explains how smart capabilities from five base technologies influence the Industry 4.0 context.		
Bag et al. (2021)	The authors examine the effect of Industry 4.0 adoption on advanced manufacturing capabilities and its outcomes for sustainable development. This author's work was important to identifying this gap in the research.		
Papadopoulos et al. (2020)	The authors discuss and highlight the limited evidence in the literature regarding the role of Digital Technologies in enhancing performance in Small and Medium Enterprises for dealing with the consequences of extreme events, such as COVID-19. This discussion highlights this research gap.	Research Gap 2: Lack of research empirical validation that Industry 4.0 adoption improves companies' resilience in times of crisis such as COVID-19.	Our research contributes to the evolution of the theory of I4.0 and the resilience aspect by developing an empirical study and contributing to filling "Research Gap 2".
Shen et al. (2020)	The authors discuss how collaborative intelligent manufacturing technologies can help to address challenges in the context of COVID-19. The authors don't develop an empirical study. The lack of empirical work in this context highlighted this research gap.		
Hopkins (2021)	The author develops a survey to measure the level of adoption of key I4.0 technologies in the supply chain (SC). The author argues that the technologies investigated will play critical roles in the post-COVID recovery, providing a new digital roadmap for the challenging years ahead. The research gap identified corroborates the authors' proposition that I4.0 technologies are fundamental for companies' resilience and recovery.		

Authors	Main contribution in relation to research gaps	Research gap	How the present study contributes to addressing this research gap
Narayanamurthy & Tortorella (2021)	The authors verify the moderating role of I4.0 base technologies on the relationship between COVID-19-related implications for working and employees' performance. The author's results present evidence regarding I4.0 during COVID-19, thus corroborating our research gap.		
Spieske & Birkel (2021)	The authors highlight the lack of literature regarding the link between I4.0 and SC resilience. The authors develop an SLR with the intention to fill this gap.		
Chowdhury & Quaddus (2017)	The authors develop a measurement instrument for SC resilience. Additionally, the authors' findings affirm that the SC resilience scale better predicts SC operational vulnerability and performance.	Research Gap 3: Lack of research empirically validating the assertion that companies' resilience improves their performance.	This research contributes to the evolution of the literature concerning resilience, specifically studying SC resilience in a new context, proposing I4.0 as an antecedent during the COVID-19 crisis.
Baz & Ruel (2020)	The authors develop and conduct a survey during the COVID-19 outbreak. The findings reveal the mediating role of supply chain risk management practices and their prominent role in fostering supply chain resilience and robustness.		
Queiroz et al. (2022)	The authors develop and conduct a survey during the COVID-19 outbreak to study an original model to explore antecedents of SC resilience, considering SC alertness as a key factor to support resilience.		

The remainder of this article is structured as follows. Section 2 consolidates the literature regarding the theoretical background and the hypotheses proposed. Section 3 describes the research methods used. The findings are presented in Section 4 and discussed in Section 5. Finally, Section 6 presents the conclusions, including theoretical and practical implications.

3.2 THEORETICAL BACKGROUND AND HYPOTHESIS DEVELOPMENT

This section addresses the theoretical background regarding the effects of the COVID-19 pandemic on manufacturing companies' performance through I4.0 approaches. This study outlines a hypothesis-based model to investigate whether the implementation of I4.0 base technologies enables the routinization of smart manufacturing practices, thus mediating the development of smart capabilities, providing companies with the necessary resilience attributes to respond better to the adverse effects of the pandemic. This research hypothesizes that resilience characteristics contribute to performance stability, mitigating the negative effects of the COVID-19 crisis. Therefore, the PBV (BROMILEY; RAU, 2016) is used to explain how

I4.0-derived practices can help manufacturing companies mitigate the impacts of the COVID-19 pandemic on operations and performance.

3.2.1 Linking I4.0 approaches, resilience, and performance stability in times of crisis: the practice-based view (PBV)

I4.0 enables manufacturing companies to develop resilience characteristics and performance improvement paths (TORTORELLA et al., 2020). I4.0 base technologies' implementation triggers smart manufacturing practices and the development of development unique smart capabilities. The PBV is used to support the hypothesis that technological change helps companies establish smart practices, which mediates the development of smart capabilities, resilience, and performance stability during times of crisis.

In this context, the term 'practice' refers to a defined activity or set of activities that various companies might adopt, e.g. digitalization (BROMILEY; RAU, 2016). This research defines smart manufacturing practices as being based on six pillars (KUSIAK, 2018): manufacturing technology and processes; resource sharing and networking; data; predictive engineering; sustainability; and materials. Based on these pillars, this study defines smart manufacturing as a bundle of practices linked to production system autonomy, energy efficiency, flexibility and customization, vertical integration and data management, and internal traceability (FRANK et al., 2019). This study assumes that smart manufacturing practices have developed in line with the recent evolution of the I4.0 concept, the roots of which initially emerged from advanced manufacturing systems and their connections with other business dimensions of companies (DALENOGARE et al., 2018; FRANK et al., 2019). Smart manufacturing enables companies to combine internal (manufacturing assets) and external resources (I4.0 base technologies). Smart manufacturing allows companies to focus on their core competencies and share capabilities for product innovation in joint efforts to develop products and complementary assets, creating greater added value (FRANK et al., 2019).

Smart manufacturing practices drive companies towards new techniques and digital procedures that enable, in the context of operations management, the development of unique smart capabilities, such as product and process innovation, digital servitization, real-time capabilities (e.g. real-time logistics flow visibility), and autonomy. Therefore, smart capabilities are the most valuable abilities enabled through the implementation of smart manufacturing practices to achieve a predefined goal. For example, IoT enables the internal traceability of parts and processes in an assembly line, such as the real-time capability to measure the humidity and temperature of the assembly components of a new product.

Previous studies, such as Marcucci et al. (2021), have found that key I4.0 technologies positively impact resilience. However, these studies have not addressed the impacts of specific I4.0 topics, such as smart manufacturing practices and capabilities, on internal manufacturing resilience. Rapidity, robustness, redundancy, and resourcefulness are characteristics of resilience that allow manufacturing companies to respond quickly to disturbances without suffering severe performance deterioration (KRISTIANTO et al., 2017).

This research adopts the definition of resilience proposed by Bryce et al. (2020), in which resilience is a process by which organizations try to anticipate and respond to external dangers continuously, rather than waiting to deal with their outcomes. Therefore, resilience reflects the effectiveness of implemented practices and development of capabilities in the context of operations and performance stability in times of crisis.

Our research proposal investigates whether the base technologies of I4.0, such as IoT, the cloud, big data, and data analytics, lead to product innovation and operational excellence through smart manufacturing, affording better organizational responses, based on resilience attributes, to disruptions such as the COVID-19 pandemic.

Therefore, the PBV is used herein to explain the effects of smart manufacturing practices (based on I4.0 base technologies) on resilience development and performance stability. Bromiley and Rau (2016) first proposed the PBV to evaluate the entire range of firm and unit performance based on exchangeable practices (BAG et al., 2021). The PBV offers operations management research an approach that is compatible with the adoption of imitable practices to explain the entire range of ordinary performance (UMAR et al., 2022a). The PBV proposes that, due to bounded rationality, companies often do not use all the available techniques and technologies that might benefit them (BROMILEY; RAU, 2014). This research considers this to be a reality for manufacturing companies in the I4.0 context. This view is relevant to this study, since it predicts that any company could develop and implement I4.0 approaches, such as smart manufacturing practices and capabilities, to create and sustain resilience in times of crisis.

3.2.1.1 The impact of the COVID-19 pandemic on manufacturing companies

The slowing down of the global economy due to the loss of production caused by the COVID-19 pandemic led to disruptions in global supply chains (IBN-MOHAMMED et al., 2021). Companies relying on worldwide supply chain inputs also started to experience reductions in production (MCKIBBIN; FERNANDO, 2020). Another factor is that limited transport between countries slowed the global economy (GOVINDAN et al., 2020), while customers' new concerns also shifted usual market consumption patterns (HE; HARRIS, 2020). In this context, manufacturing managers need to be aware of the optimal mechanisms to adjust the supply and demand of resources and of techniques to optimize their distribution networks and adapt to changes in demand (RIO-CHANONA et al., 2020). Such decisions must be made during the response and recovery phases of the COVID-19 pandemic, most likely at the national or regional levels (PAPAGIANNIDIS et al., 2020). These changes affected global financial markets, and the stock index plummeted (CURRIE et al., 2020).

Bartik et al. (2020) show in their empirical study that businesses were deeply affected by the COVID-19 pandemic. Their research results underscore the financial fragility of many small businesses. Their study found that 43% of businesses were temporarily closed and that employment fell by 40%. These results suggest that many such firms faced financial problems during the pandemic and were forced to cut expenses dramatically, take on additional debt, or declare bankruptcy. These findings highlight the negative effect that the COVID-19 pandemic had on organizations' financial systems.

Although not yet empirically tested in the literature, several effects of the COVID-19 pandemic have been discussed, beyond the financial difficulties that organizations have been experiencing. Currently, several effects of the COVID-19 crisis continue to damage manufacturing operations and supply chains, including sudden changes in supply related to products, loss of contracts and sales (VENKATESH, 2020), the necessity for sanitization in the workplace (KUCKERTZ et al., 2020), long delays in receiving supplies and delivering products (KUMAR et al., 2020), a shortage of workforce and reduced capacity (QUEIROZ et al., 2020), the necessity of remote working (CARROLL; CONBOY, 2020), sudden changes in demand for products and consumers' buying patterns (Sharma et al., 2020), and limited capability concerning human, technological, logistical, and managerial aspects due to limited resources and access (BRYCE et al., 2020; HOPKINS, 2021; QUEIROZ et al., 2020; SARKIS et al., 2020).

Although the existing literature points out that SCs, in general, have been negatively affected by the COVID-19 outbreak, leading to a drop in sales and a lack of the supplies needed for production, some business models have benefited, such as the production of hygiene products and personal protection products (e.g. masks). The aim of the present research, however, is to consider only companies that have been negatively affected by the pandemic, in order to better fit the hypothesized model. Therefore, to verify whether the companies included in the sample in the present study are indeed part of chains that have been negatively affected by the COVID-19 outbreak, the following hypothesis is formulated:

H1. The COVID-19 pandemic has had a negative impact on manufacturing companies' performance.

3.2.1.2 Implementation of I4.0 technology and smart manufacturing practices

The approach to I4.0 taken in the present study is based on the concepts of base technologies and front-end technologies. This is a categorization based on Frank et al.'s (2019) framework for I4.0 adoption patterns. Base technologies are dealt with in hypothesis 2 and front-end technologies in hypothesis 3 (e.g., AI, co-bots, additive manufacturing, autonomous lines). Therefore, despite the existence of other important studies which present a range of I4.0 technologies (see Table 1), they have not classified and systematized these sets of technologies into relationship categories (supporting the perspective on I4.0 taken in this article). Four base technologies constitute the pillars of the I4.0 concept, providing a wide range of smart manufacturing applications: IoT; the cloud; big data; and data analytics (e.g. the use of multivariate data analysis and advanced AI algorithms) (FRANK et al., 2019). I4.0 base technologies enable smart manufacturing practices (KUSIAK, 2018) and reflect I4.0 implementation in the company. Frank et al. (2019) propose a framework summarizing I4.0 implementation patterns. In this framework, these four base technologies support the use of front-end technologies, enabling the development of smart manufacturing practices.

I4.0 technologies provide a wide range of applications and entail changes in manufacturing practices through adopting the smart manufacturing concept (KUSIAK, 2018). From IoT technologies, opportunities arise for smart manufacturing practices, such as production system autonomy, flexibility, and internal traceability. From the cloud, options arise for digital customization and vertical integration. Energy efficiency and management opportunities arise from big data and data analytics. Self-correcting manufacturing processes, work planning and manuals' digitalization, energy-efficient warehousing intralogistics, resource-efficient industrial laundry, and energy management in smart grids in processing industries are all examples of smart manufacturing practices enabled by the four I4.0 base technologies adopted in this survey (MAC DOUGALL, 2016).

The second hypothesis intends to test the existing theory and present an empirical investigation of the I4.0 base technologies' relationships and their positive effects on the development of smart manufacturing practices, based on Frank et al.'s (2019) framework. Therefore, based on previous studies showing that I4.0 technologies enable companies' smart manufacturing practices, this study's second hypothesis is as follows:

H2. I4.0 base technologies' implementation in manufacturing companies is positively associated with smart manufacturing practices.

3.2.1.3 The mediating effect of smart manufacturing practices on developing smart capabilities

The smart manufacturing practices addressed in this study align with the I4.0 technologies proposed by Frank et al. (2019). The practices assessed in this study are the autonomy of the production system, energy efficiency, flexibility, customization, vertical integration, data management, and internal traceability. Furthermore, this research investigates whether smart manufacturing practices support the development of smart capabilities (e.g. real-time parts visibility) in coping with the COVID-19 crisis and, consequently, create resilience and support performance stability.

Implementing core practices focusing on digital value creation can lead to excellence by providing unique digital competencies for manufacturing, i.e. smart capabilities. The PBV asserts that a bundle of defined practices within key organizational activities might significantly influence firm performance (BROMILEY; RAU, 2016). However, specific manufacturing practices can also be associated with other independent variables besides performance, e.g. smart capabilities (BAG et al., 2021). Thus, smart manufacturing practices can, in turn, support the unique and advantageous development of smart capabilities.

Smart capabilities are defined as the unique ability to reconfigure tangible and intangible assets of the manufacturing system based on I4.0 approaches. Smart capabilities result from implementing smart manufacturing practices that are feasible due to specific I4.0 base technologies. For example, Helo et al. (2019) take a set of I4.0 technologies for vertical integration practices in a sheet metal manufacturing company. Tools such as genetic algorithms and IoT machinery, service-oriented architecture (SOA)/REST API, and C# programming via the Microsoft Azure private cloud system were applied to develop real-time capabilities (real-time production analysis and planning) with digital servitization (cloud-based production scheduling). Bag et al. (2021) investigate I4.0-related practices and smart capabilities' development through the PBV lens. They find that firms with a high degree of I4.0 adoption demonstrate a higher degree of smart capabilities. This research assumes that implementing smart manufacturing practices based on I4.0 technologies mediates the development of smart capabilities. Smart capabilities, such as the real-time monitoring and connectivity of manufacturing assets and remote working, were critical to operations' reconfiguration in the face of the sudden COVID-19 crisis. Therefore, smart capabilities are critical to companies' performance stability in production environments facing rapid and dynamic changes, e.g. the COVID-19 pandemic. Therefore, the third hypothesis is as follows:

H3. Smart manufacturing practices are positively associated with the development of smart capabilities.

3.2.1.4 Development of smart capabilities and manufacturing companies' resilience characteristics

During times of crisis, companies require unique capabilities to enable rapid reconfiguration of operations and adaptability to mitigate unexpected supply chain behavior. The smart capabilities included in this study are based on Bueno et al.'s (2020) research. These capabilities include: promoting coordination in processes; developing a wide range of innovative products and processes; developing a high level of automation and autonomy for manufacturing machines, systems, and decision processes; digitalizing data collection and connectivity infrastructure; developing operational and managerial processes-as-a-service; and whether companies have a digital culture incorporating I4.0 technologies at all employee levels. This research investigates whether prior smart capability creation leads to better company resilience during the COVID-19 pandemic.

In manufacturing operations, sustainable competitive advantages and performance stability may be achieved through a competitive position that best exploits unique capability strategies made possible by I4.0 implementation. Through I4.0 technologies, companies embed smart resources in their practices, opening up new opportunities to carry out manufacturing operations and management in a novel, improved manner. Subsequently, smart capabilities arise from unique processes, paths, and positions over time and through practice.

Companies can build several capabilities in their response to shocks such as the COVID-19 pandemic. This response capability is directly linked to the development of resilience characteristics (KRISTIANTO et al., 2017). For example, the smart capability of digitalized data collection minimizes workers' presence on the shop floor. It enables better flexibility in worker scheduling on the shop floor to deal with social distancing during the critical period of COVID-19 propagation. This example represents a flexibility-based resilience characteristic triggered by the digitalization capability. Thus, this research considers that manufacturing resilience attributes are leveraged by smart capabilities.

Therefore, creation of smart capabilities can positively impact manufacturing companies' response and resilience in times of disturbance, such as the COVID-19 pandemic. Accordingly, our fourth hypothesis is as follows:

H4. Creation of smart capabilities positively impacts manufacturing companies' resilience during times of crisis.

3.2.1.5 Manufacturing companies' resilience and performance in times of crisis

The hypotheses posited above suggest that companies' resilience can be mediated by mastering technologies, practices, and smart capabilities associated with I4.0. The quality of companies' response and agility in times of crisis are important variables for operations management, and is known as responsiveness. In "normal" times responsiveness permits organizations to respond to fluctuations in customer demand, thus improving lead time and profits. In times of crisis, companies' responsiveness becomes a variable of great complexity and is considered of the utmost importance for manufacturing operations management (KRISTIANTO et al., 2017). For example, being highly responsive can enable a company to survive supply chain disruption. The COVID-19 pandemic showed that resilience to supply chain disruptions needs to be evaluated as an issue of civic and industrial survival in the face of extraordinary events. The example of the COVID-19 pandemic clearly shows the necessity of responsiveness, robustness, and resilience.

The literature shows that companies aiming to improve their performance need to constantly assess their supply chain design and proactive and reactive approaches (reconfiguration) to combat supply chain vulnerabilities (CHOWDHURY; QUADDUS, 2017). Resilience relates to manufacturing and supply chain companies' ability to carry out their planned operations and ensure global performance stability following a disruption (or a series of disruptions) (BAZ; RUEL, 2020; NAIR; VIDAL, 2011; QUEIROZ et al., 2022; SIMCHI-LEVI et al., 2018).

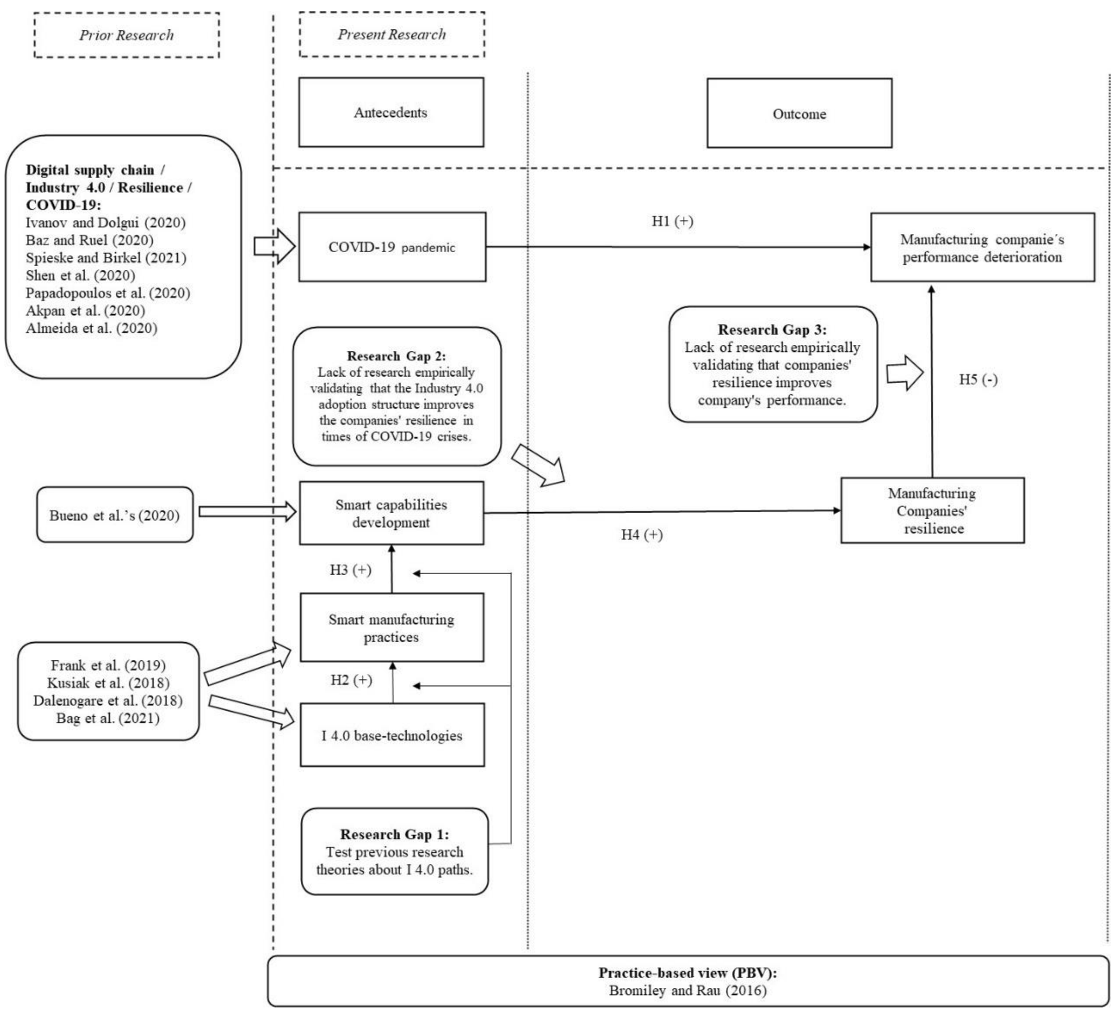
Rajesh (2021) links resilience characteristics to positive performance effects. Consequently, this research assumes that operational performance (e.g. productivity, quality, wastage), supply chain performance (e.g. raw material shortage, lead time), and financial performance are associated with manufacturing companies' resilience during the COVID-19 pandemic. Therefore, this research assumes that resilience mitigates the effect of the negative impacts of the COVID-19 pandemic on manufacturing operations and performance. According to Kristianto et al. (2017, p. 607), "…the main strategy to achieve this is to respond to the disruptions by having the manufacturing capabilities to be either flexible or reliable. The combination of flexibility and responsiveness is called 'resilience', and the combination of reliability and responsiveness is called 'robustness'".

Accordingly, it is expected that when I4.0 improves the company's responsiveness, this enables the company to make decisions and execute actions to ensure that his operational and financial performance remains stable despite major disruptions in the global supply chain. Therefore, manufacturing companies' flexibility, reliability, robustness, and responsiveness can support the company's resilience. According to Ivanov and Dolgui (2020), supply chain and manufacturing companies' survival during extraordinary events goes beyond a narrow understanding of performance based on profits or revenues: these companies need to secure the provision of goods and services by being highly resilient. Accordingly, the fifth and final hypothesis is proposed:

H5. Manufacturing companies' resilience positively impacts their operational and financial performance.

This study's conceptual model, including hypotheses, is shown in Figure 3.1.

Figure 3.1 - Research model and hypotheses.



3.3. RESEARCH METHODS

This study uses a survey research methodology to evaluate the implementation of I4.0 technologies to develop smart manufacturing practices and smart capabilities in supporting manufacturing companies' response to the COVID-19 pandemic. The research model (Fig. 1) was developed based on a literature review to illustrate the main elements investigated in this study and its hypotheses. According to Fowler (2013), the survey method involves collecting information from individuals concerning the social units to which they belong. Thus, a survey research sampling process determines information about large populations with a known level of accuracy. This study utilizes an exploratory survey. An exploratory survey is suitable during the early stages of research into a phenomenon to gain preliminary insights into a topic and to provide evidence for more in-depth research (STAPLETON, 2019). The effects of the COVID-19 pandemic is a recent topic, and this research is among the first to present evidence that I4.0 can make organizations more responsive and resilient when facing crises such as pandemics.

3.3.1. Sample selection and data collection

The study sample is drawn from the Brazilian manufacturing industry. The questionnaire was administered using the SurveyMonkey platform and sent to companies' e-mail addresses, aimed at practitioners dealing with I4.0 implementation in their companies. Survey questionnaires were administered from October to December 2020. However, respondents were asked to consider the period between March and November 2020 when responding to the survey. Two control variables were used: implementation of I4.0 solutions; and role responsibility (analysts, managers).

COVID-19 countermeasures are often managed on the tactical and strategic levels of organizations (analysts and managers); they also deal with I4.0 implementation issues (therefore possessing knowledge about these processes and technologies). Therefore, the focus was on reaching respondents who were analysts and managers (middle and top levels). Hence, non-probabilistic sampling was used (VEHOVAR et al., 2016). Follow-ups were sent every 15 days over three months to those contacts who had not responded, in order to increase the response rate. LinkedIn was also used to increase the number of responses, based on the research team's network, creating customized requests for participation, and a providing a detailed explanation of the study's purpose and benefits (VEHOVAR et al., 2016). Ultimately, from the 1,500 questionnaires sent out, 349 were returned (a response rate of 23.7%). However, only 207 of these responses were complete and usable. According to Holtom et al. (2022), our response rate is quite adequate. Data gathering was performed during different periods (50 days,

n = 207), resulting in three sub-samples. Kruskal–Wallis's ANOVA method was used as a non-parametric test (HAHS-VAUGHN; LOMAX, 2020) to test the means between the different periods for respondents' answers. These test results indicated no difference ($p > 0.05$) between the three groups, meaning that there is no statistical evidence that each sample segment is significantly different from the rest of the population (HAHS-VAUGHN; LOMAX, 2020).

Regarding respondents' characteristics, 14.4% were either a manager or a director, 30.3% were either supervisors or coordinators, and 55.4% were analysts. Further, 35.4% of respondents worked in companies with more than 5,000 employees, and the survey addressed different manufacturing industries. Table 3 measured the companies' knowledge of the I4.0 concept. The degree of technology implementation was measured in the constructs "I4.0 base technologies (IBT)" and "second-order, reflective-formative constructs" (see Tables 4 and 5). The results suggest that most of the companies analyzed, even if they implement I4.0 technologies, do not fully understand the global concept of I4.0. Many companies were already investing in technologies even before the I4.0 concept appeared in the literature. Many companies' understanding of Industry 4.0 is limited to the implementation of only advanced technologies such as robots and artificial intelligence. The complete breakdown of respondents' characteristics and organizational profiles regarding I4.0 is shown in Tables 3.2 and 3.3.

Table 3.2 - Sample characteristics (n=207).

	(*n*)	**Percentage (%)**
Industrial sector		
Food and drink	32	15%
Metal mechanical	22	11%
Mining	22	11%
Automotive and aviation	12	6%
Agriculture	9	4%
Consumer goods	3	1%
Energy	9	4%
Chemicals	9	4%
Software and technology	13	6%
Transport	10	5%
Paper and cellulose	8	4%
Petrochemicals	5	2%
Electronic	3	1%
Transport	10	5%
Tobacco industry	1	0,5%
Others	39	19%
Organization size		
≤5,000 employees		64.6%
>5,000 employees		35.4%
Respondent's role		
Analyst		55.4%
Supervisor or coordinator		30.3%
Manager or director		14.4%

Table 3.3 - Companies' profiles regarding I4.0 (n=207).

	Percentage (%)
Degree of company knowledge concerning the global concept of I4.0	
Fully engaged with concrete projects within the concept of I4.0	32.3
Has already developed some pilot project(s) for implementing advanced I4.0 technologies	44.1
Some up to date knowledge regarding Industry 4.0 concepts	12.8
Not much familiarity with the global concept of I4.0	9.7
No knowledge of the Industry 4.0 concept	1.0
Company innovativeness category in relation to I4.0[b]	
Innovators	25.6
Early adopters (adoption before most companies)	30.8
Early majority (adoption in line with sector-leading companies)	20.5
Late majority (adoption after most companies)	20
Laggards (last to adopt)	3.1

3.3.2 Measures and scales

The questionnaire applied in this research followed Fowler's (2013) and Dillman et al.'s (2014) recommendations. Regarding question formulation, language corresponding to the respondents' level of understanding was considered. A closed question format was chosen to allow for immediate analysis. The research instrument was structured in five parts. The first part asked for organizational and respondent data. The second part verified the degree of implementation of I4.0 base technologies' and associated smart manufacturing practices. The third part addressed the manufacturing companies' resilience and performance in facing the COVID-19 pandemic. In the fourth part, this research evaluated the organization's perception of the effects of the COVID-19 pandemic. The fifth part was related to development of smart capabilities. A seven-point Likert scale (1 = "Strongly disagree" to 7 = "Strongly agree") was used for all items.

Our questionnaire was developed using an initial set of constructs and items adopted from Frank et al. (2019), Dalenogare et al. (2018), Kusiak (2018), and Bag et al. (2021) concerning I4.0 and smart manufacturing constructs. The questions on the COVID-19 construct were developed from articles addressing the effects of the COVID-19 pandemic in manufacturing operations management, as discussed in Section 2. These questions were based on recent studies by Bryce et al. (2020), Ivanov and Dolgui (2020), Queiroz et al. (2020), McKibbin and Fernando (2020), Govindan et al. (2020), Papagiannidis et al. (2020), Kuckertz et al. (2020), and Hopkins (2021). The items related to the smart capabilities construct were based on Bueno et al.'s (2020) systematic literature review (SLR). The manufacturing companies' resilience construct was developed from studies by Kristianto et al. (2017), Rajesh (2021), and Castro and Zermeno (2021). Finally, performance measures were based on the SLRs of Bueno et al. (2020), Moeuf et al. (2018), and Buer et al. (2018).

3.3.3 Data analysis

Composite-based structural equation modeling was used for data analysis and to test the hypotheses to generate empirical findings. Partial least squares-structural equation modeling (PLS-SEM) was selected considering that it is a suitable approach for dealing with composite models (not factor models) in large systems involving dozens of constructs and indicators and examining relationships that have not been established or that lack prior knowledge (HENSELER, 2021; LATAN; NOONAN, 2017; MEHMETOGLU; VENTURINI, 2021). In the present study, the proposed model is still primitive and lacks empirical support. In addition, PLS-SEM is useful when dealing with formative or composite indicators and when aiming to examine causal-predictive relationships between variables. Given the nature of the constructs in this study, which are formative or composite, PLS-SEM is considered an appropriate technique (HENSELER, 2021; LATAN; NOONAN, 2017; MEHMETOGLU; VENTURINI, 2021).

Although PLS-SEM follows non-parametric (i.e. distribution-free) assumptions, this research considers several key requirements when using this method: (i) the sample size must be sufficient for model estimation; (ii) there must be no multicollinearity between predictors; and (iii) the model must be specified appropriately (HAIR et al., 2022; HENSELER, 2021). The minimum sample size required to estimate the model was found to be 138 cases (effect size = 0.15, required power level = 0.95, significant level = 0.05, number of predictors = 5), which was met in this study. In addition, it was ensured that the model was correctly specified through a series of literature reviews. No inverse relationship between the path coefficients was found, indicating that the model is free from model specification errors (WHITTAKER; SCHUMACKER, 2022). Finally, the best practice recommendations for reporting the PLS-SEM analysis results were followed, including examining several biases in the survey method, measurement model assessment, structural model assessment, hypothesis testing, and robustness tests (HAIR et al., 2022; LATAN, 2018).

A series of data cleaning processes was carried out before estimating the model and testing the proposed hypotheses. First, straight-lining and missing values were verified. There were no straight-lining answers or missing values found in this case. Second, the data was checked for outliers through the *z*-score calculation, which did not find a *z*-value > 2.58. Therefore, it was concluded that the data are free from outliers and missing values. These procedures were essential to avoid bias in parameter estimation.

3.3.3.1 Non-response bias

This research tested for non-response bias to ascertain whether the respondents who participated in this survey differed from those who did not participate (CLOTTEY; BENTON, 2020; VOGEL; JACOBSEN, 2021). This bias poses a threat in this survey method, given that participation was voluntary. To detect this bias, two approaches were used. First, early responders were compared to late responders. No difference was found between the two sample groups based on the *t*-test ($p > 0.05$) for each variable in the model. Therefore, it was concluded that this bias does not exist. To substantiate this evidence, those who never refused to participate in the survey were compared with those who initially declined (FULTON, 2016). Again, no difference was found between the two groups based on the *t*-test ($p > 0.05$). Therefore, it can be concluded that the data are free from this bias.

3.3.3.2 Common method variance (CMV)

CMV usually arises when the same respondent assigns numerical values on a psychometric scale, both for the antecedent constructs (e.g. manufacturing companies' response) and consequence constructs (e.g. manufacturing companies' performance) (BOZIONELOS; SIMMERING, 2022). Thus, it is essential to adopt procedures that avoid CMV. This study reduced this bias by randomly sorting the items for each construct. It was explained to each respondent that their name and the company information would remain anonymous.

The marker variables approach was used to detect bias through confirmatory factor analysis (CFA) (SIMMERING et al., 2015). This research did not find any significance for the marker variables through small correlations with the main constructs and the marker model resulted in a poor goodness of fit. It was therefore concluded that CMV does not exist in our measurements.

3.4 RESULTS

The SmartPLS 4 (RINGLE et al., 2022) software was used for data analysis, as the most well-known PLS software for overall model estimation. Specific settings were created, such as selecting a path weighting scheme and standardized results in the PLS algorithm. For bootstrapping, 10,000 resamples were used with parallel processing, as well as a bias-corrected and accelerated (BCa) interval at the 5% significance level (one-tailed test) to test the hypotheses. The following subsections present the results of both the measurement and structural models.

3.4.1 Assessing the formative measurement model

Our model uses formative constructs and type II second-order constructs (reflective-formative) (SCHUBERTH et al., 2020) concerning the smart manufacturing practices construct, i.e. vertical integration and data management, internal traceability, production system autonomy, energy efficiency, and flexibility and customization.

A formative measurement model was chosen due to the characteristics of the items that make up each construct. This does not presuppose covariance, but seeks to generate a summative indicator (HAIR et al., 2022; HENSELER, 2021). For example, in the “COVID-19 pandemic” construct, the items comprised “our industrial sector”, “our suppliers”, “our competitors”, “our demand”, and “our factory […] was/were affected by the COVID-19 pandemic.”

Although a correlation between these factors is possible, this method aims to generate an indicator that expresses in general terms how the company and other stakeholders have been affected by the COVID-19 pandemic, hence the choice of a formative model.

In order to ensure that there are no specification errors in the selection of indicators, confirmatory tetrad analysis (CTA) was performed, which confirmed the possibility of using models of a formative nature for the constructs “manufacturing companies’ performance”, “Industry 4.0”, “smart manufacturing practices”, “smart manufacturing capabilities”, and “companies’ resilience” (HAIR et al., 2018). These constructs were determined to be formative based on the characteristics of the items that compose them, as illustrated in the “COVID-19 pandemic” construct.

The formative measurement model was assessed following the rules of thumb proposed by Hair et al. (2022). First, the significance of the “weight” of each formative indicator forming the constructs in the model was examined through a bootstrapping procedure. A set of indicators that met this criterion ($p < 0.05$) was found; however, several indicators were excluded because they were not significant, with a loading factor less than 0.5 (CR2, CR3, CR4, CR5, and CR6). Furthermore, it was ensured that each item’s variance inflation factor (VIF) value was less than 3.3. This research found that most items had VIF values < 3.3; therefore, it was concluded that there is no multicollinearity issue between the formative indicators in the model (Lindner et al., 2020). However, since they did not meet this threshold, several items were excluded (CO1, CO2, SCD1, SCD2, SCD4, SCD5, SCD6, SCD7, and SCD8). Finally, the factor loading values for items with a significant “weight” ($p > 0.05$) were examined. Items with a factor loading value of more than 0.5 were retained to strengthen nomological validity; there were several items that met this criterion. The evaluation results of the formative measurement model are shown in Table 3.4.

Table 3.4 - Validation of formative constructs.

Construct	Item	Code	VIF	Outer weight (*p*-value)	Outer loading
I4.0 base technologies (IBT)	Internet of things (IoT)	BT1	1.344*	0.050**	0.613***
	Cloud	BT2	1.754*	0.082	0.733***
	Big data	BT3	2.704*	0.000**	0.948***
	Data analytics	BT4	2.738*	0.021**	0.892***
COVID-19 pandemic (COV)	Our suppliers were strongly affected by the COVID-19 outbreak	CO3	1.796*	0.000**	0.812***
	Our competitors were strongly affected by the COVID-19 outbreak	CO4	2.201*	0.001**	0.841***
	Our demand was strongly affected by the COVID-19 outbreak	CO5	1.954*	0.000**	0.815***
	Our factory interrupted its operations during the pandemic	CO6	1.337*	0.000**	0.739***
Companies' resilience (CRS)	We managed to deal with the sudden disruption of suppliers	CR1	1.157*	0.040**	0.414
	We had no capacity restrictions on production	CR7	1.518*	0.136	0.543***
	We were able to deal with physical distribution problems caused by the COVID-19 pandemic	CR8	2.014*	0.415	0.581***
	We were able to deal with financial constraints caused by the COVID-19 pandemic	CR9	1.761*	0.001**	0.618***
	Our company created a crisis management committee to deal with the effects of COVID-19	CR10	1.815*	0.183	0.570***
	Our organization has been responsive and flexible during the COVID-19 pandemic	CR11	2.121*	0.387	0.636***
	Our organization employed digital technologies in its operations to overcome COVID-19 pandemic challenges	CR12	1.609*	0.002**	0.687***
	Our policy of continually seeking to reduce waste has helped us to overcome the challenges of the pandemic	CR13	2.150*	0.445	0.541***
	Our organization has a risk management system in the supply chain as a way to mitigate the effects of the COVID-19 pandemic	CR14	2.580*	0.039**	0.714***
	Our organization was able to handle deliveries without touch/contact	CR15	1.697*	0.010**	0.709***
Smart capabilities development (SCD)	Our company makes efforts to develop/adopt a wide range of innovative products and processes	SCD3	1.720*	0.120	0.735***
	Our company makes efforts to develop/adopt operational and managerial processes-as-a-service (e.g., an ERP module offered in the cloud)	SCD9	2.066*	0.000**	0.921***

Construct	Item	Code	VIF	Outer weight (p-value)	Outer loading
	Our company has a digital culture and familiarity with Industry 4.0 technologies at all employee levels (from top management to the shop floor)	SCD10	1.919*	0.000**	0.885***
Smart manufacturing practices (SMP)	Production system autonomy	PSA	1.950*	0.050**	0.696***
	Energy efficiency	EE	1.896*	0.419	0.666***
	Flexibility and customization	FC	2.097*	0.251	0.705***
	Vertical integration and data management	ViDm	2.734*	0.000**	0.987***
	Internal traceability	ITr	1.743*	0.458	0.637***
Manufacturing companies' performance (MCP)	Productivity in our company has not been affected negatively by the COVID -19 pandemic	MP1	1.784*	0.000**	0.784***
	Our company's financial performance has not been affected negatively by the COVID-19 pandemic	MP4	3.149*	0.006**	0.849***
	The overall performance of our company has not been affected directly by the economy's 'opening/closing'	MP5	3.077*	0.017**	0.839***
	Our company's capacity availability was not negatively affected by the COVID-19 pandemic	MP6	2.136*	0.004**	0.796***
	The defect rate of our products did not increase during the COVID-19 pandemic	MP7	1.178*	0.036**	0.524***
	Finished product inventory levels did not decrease during the COVID-19 pandemic	MP11	1.132*	0.002**	0.503***

Notes: * VIF < 3.3; Outer weight ** $p < 0.05$; *** Outer loading > 0.5.

3.4.2 Assessing the second-order, reflective-formative construct

The reflective indicators and a second-order construct were validated using a type II (reflective-formative) method, following the procedure described by Hair et al. (2022). A two-stage approach was used, which is considered better for handling second-order constructs. In the first step, repeated indicators were used to evaluate the measurement model of these dimensional items. Composite reliability (CR) and Cronbach’s alpha (CA) values were used to evaluate internal consistency among items for each dimension construct. The CR and CA values were confirmed to be greater than 0.7. Thus, the internal consistency of these dimension constructs was confirmed (BANDALOS, 2018; NUNNALLY; BERNSTEIN, 1994).

Furthermore, convergent validity was assessed through loading factor and average extracted variance (AVE) values. The AVE is the mean value of the squared item loadings associated with the construct, and an AVE value of 0.50 or higher is adequate for each construct to explain more than half of its correspondent items (HAIR et al., 2022; HENSELER, 2021). Meanwhile, item loadings should equal to or above 0.708 for a latent variable to explain a substantial part of each indicator's variance (BANDALOS; FINNEY, 2019; NYE, 2022). If deleting the item increases the CR and AVE, items with outer loading below 0.4 should be considered for removal. Finally, discriminant validity was assessed using the heterotrait-monotrait (HTMT) ratio as well as HTMT2 (HENSELER, 2021). In this research, the values for the HTMT and HTMT2 ratios were found to be greater than the 0.85 threshold, based on the multitrait-multimethod (MTMM) matrix (see Table 6), providing evidence of discriminant validity.

To validate "smart manufacturing practices" and its associated dimension (a type II second-order construct), reflective constructs were used. The results are of this analysis are presented in Tables 3.5 and 3.6.

Table 3.5 - Validation of reflective constructs.

Construct	Item (regarding degree of implementation)	Code	Outer loading	CA	CR	AVE
Production system autonomy (PSA)	Industrial robotic systems	PSA1	0.927*	0.801	0.909	0.833
	Collaborative man/machine work (collaborative robots)	PSA2	0.898*			
Energy efficiency (EE)	Energy efficiency monitoring system	EE1	0.969*	0.934	0.968	0.938
	Energy efficiency improvement system	EE2	0.968*			
Flexibility and customization (FC)	Additive manufacturing (production line with 3D-printers)	FC1	0.873*	0.746	0.887	0.796
	Flexible and autonomous production lines	FC2	0.911*			
Internal traceability (ITr)	Raw material identification and traceability	ITr1	0.947*	0.882	0.944	0.895
	Identification and traceability of components of final products	ITr2	0.945*			
Vertical integration and data management (ViDm)	Regulatory process control (e.g., sensors, actuators, PLCs)	ViDm1	0.715*	0.915	0.929	0.570
	Process monitoring, control, and supervision (SCADA)	ViDm2	0.796*			
	Production planning and control systems integrated with equipment (MES)	ViDm3	0.760*			
	Business process management systems integrated with manufacturing systems (e.g., ERP)	ViDm4	0.574*			
	Virtual commissioning for automation systems (e.g. PLCs)[a]	ViDm5	0.775*			
	Communication and integration between machines (M2M)	ViDm6	0.800*			
	Artificial intelligence for predictive diagnostics in equipment	ViDm7	0.791*			
	Artificial intelligence for production planning and control (e.g., big data analytics, data mining, machine learning, among others)	ViDm8	0.774*			
	Process simulation to aid decision-making (e.g., digital manufacturing)[b]	ViDm9	0.785*			
	Automatic identification of non-conformities in production	ViDm10	0.751*			

Notes: CA = Cronbach's alpha; CR = composite reliability; AVE = average variance extracted; * $p < 0.05$.

[a] By using the virtual commissioning solutions, the programmable logic controller (PLC) codes can be debugged in a virtual environment before downloading the actual equipment. Simulating and validating the automation equipment can virtually confirm that it will work as expected.

[b] In Smart Manufacturing, data management systems and simulation technologies are used jointly to optimize manufacturing before starting production and supporting the ramp-up phases.

In line with the rules of thumb mentioned earlier, CA and CR values were obtained for all dimensions greater than 0.70. Additionally, the AVE values were found to be greater than 0.50, and the outer loading value for each indicator was more than 0.708 for the dimensions of the second-order constructs (see Table 5). Therefore, it was concluded that convergent validity and internal consistency reliability are demonstrated. Although the ViDm4 item had an outer loading value below 0.708 (0.574), it was decided to keep it in the model because it did not damage the global convergent validity of its construct.

Table 3.6 - Discriminant validity: HTMT and HTMT2 ratios

Construct	**EE**	**FC**	**ITr**	**PSA**	**ViDm**
Energy efficiency (EE)	*(0.85)*	0.713	0.610	0.553	0.569
Flexibility and customization **(FC)**	0.567	*(0.85)*	0.774	0.816	0.609
Internal traceability (ITr)	0.552	0.609	*(0.85)*	0.703	0.564
Production system autonomy (PSA)	0.610	0.814	0.562	*(0.85)*	0.681
Vertical integration and data management (ViDm)	0.711	0.773	0.701	0.680	*(0.85)*

Notes: Diagonal and bold elements are cut-off values for HTMT and HTMT2. Below the diagonal are the HTMT2 values. The values above the diagonal show the HTMT values.

Table 6 shows the results for discriminant validity. The HTMT values obtained were less than 0.85 (see above the diagonal line in Table 6). Therefore, it was concluded that discriminant validity is demonstrated in this study. To strengthen this evidence, HTMT2 was examined. All constructs displayed HTMT2 values lower than the predefined threshold of 0.85, therefore corroborating the previous discriminant validity evidence (see below the diagonal line in Table 6).

After validating these dimensions of the reflective measurement model, latent variable scores were extracted from these dimensions to form "smart manufacturing practices" as a new formative construct. The next step was to evaluate the structural model and test the hypotheses.

3.4.3 Assessing the structural model

Prior to testing the hypotheses, the structural model was assessed through several core metrics to demonstrate model fit. R-square (R^2) and adjusted R^2 values were calculated to show the percentage of variance explained and effect size (f^2), as well as the inner VIF to show the strength of the relationship between the variables (i.e., between a predictor and an outcome) and the model tested was found to be free of multicollinearity (see Table 7).

R^2 values range from 0 to 1, and results closer to 1 indicate more significant predictive accuracy of the model. The R^2 values obtained range from 0.486 to 0.654, which, according to

Cohen et al. (2003), are within the "large" category. An R^2 value greater than 0.25 is considered good in social sciences research. The R^2 values suggest that the model has excellent adequacy, except for the "smart capabilities development" → "manufacturing companies' resilience" relationship (R^2 = 0.322). The R^2 value here, related to *H4*, can be explained by the fact that "companies' resilience" cannot be fully explained exclusively by "smart capabilities development". Other manufacturing practices from interface industries, such as logistics, quality, purchasing, and finance, can also affect "companies' resilience". In addition, the f^2 values generated in the model's relationship between the two variables ranged from 0.042 to 0.574. An f^2 value of more than 0.02 indicates that the model shows a strong relationship (i.e., a true effect), while an f^2 value close to zero is insignificant and suggests bias. In this case, f^2 values greater than 0.02 were obtained, indicating the strength of the association between each predictor and outcome in this model (GRISSOM; KIM, 2012). Finally, inner VIF values < 3.3 were obtained, which demonstrates that the model is free of multicollinearity (LINDNER et al., 2020).

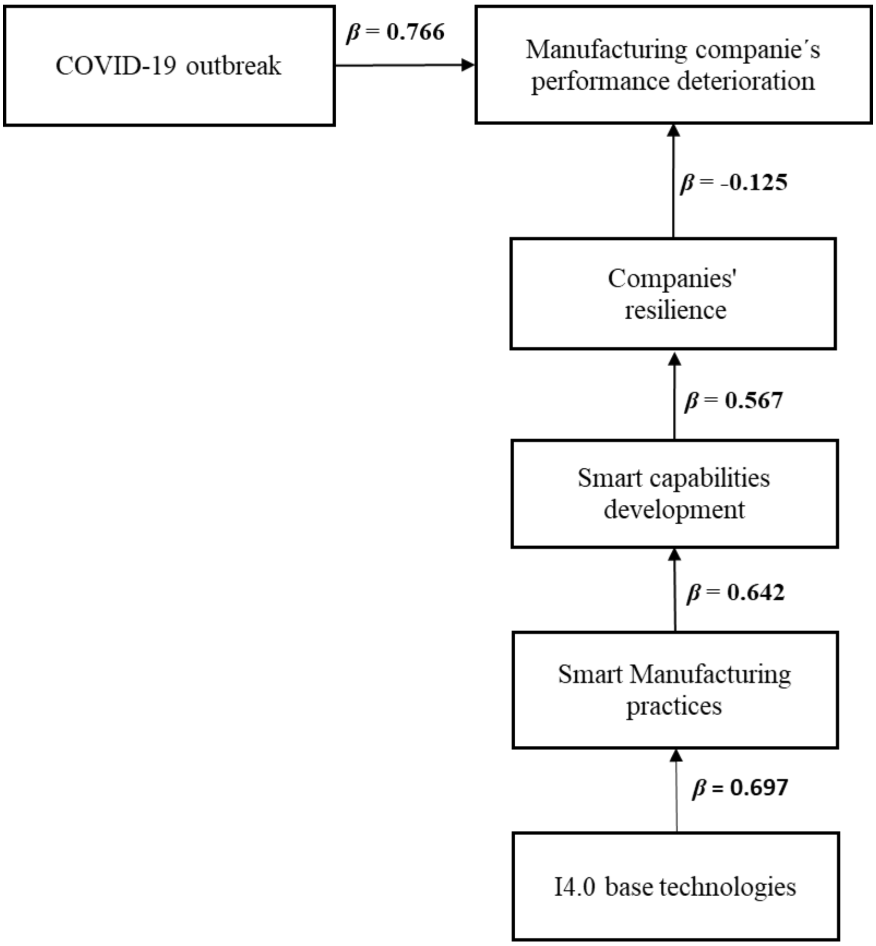
Table 3.7 - Structural model assessment.

Construct	R^2	**Adj.** R^2	f^2	**VIF**
COVID-19 pandemic **(COV)**	–	–	0.574	1.079
I4.0 base technologies **(IBT)**	–	–	0.546	1.079
Smart manufacturing practices **(SMP)**	0.486	0.484	0.303	1.000
Smart capabilities development **(SCD)**	0.413	0.410	0.474	1.000
Companies' resilience **(CRS)**	0.322	0.318	0.042	1.000
Manufacturing companies' performance **(MCP)**	0.654	0.651	–	1.000

3.4.4 Hypothesis testing

After evaluating the structural model, the hypotheses were tested using a bootstrapping approach with 10,000 subsamples and examination of the direction of the beta coefficient and the resulting significant values. A 95% confidence interval (CI) was used to accept or reject each hypothesis tested. The CI was generated at the 5% significance level (one-tailed test). Figure 3.2 illustrates the main results for the model. Ultimately, all the proposed hypotheses were empirically supported.

Figure 3.2 - Structural model results.



As shown in Table 3.8 and Figure 3.2, significant path relationships were specifically found between the variables "COVID-19 pandemic" → "manufacturing companies' performance" and "I4.0 base technologies" → "smart manufacturing practices", with beta coefficients (β) of 0.766 and 0.697, respectively, significant at $p < 0.05$ at 95% CI. Therefore, *H1* and *H2* are supported empirically. Furthermore, a path relationship was found between "smart manufacturing practices" → "smart capabilities development" → "companies' resilience" → "manufacturing companies' performance", which was significant, with beta coefficients of 0.642, 0.567, and –0.125, respectively, significant at $p < 0.05$ at 95% CI. Hence, it can be concluded that *H3*, *H4*, and *H5* are supported.

Table 3.8 - Main results of the hypothesis testing.

Structural relation	β	SD	*p*-value	95% BCa CI	Decision
***H1*: COVID-19 pandemic → Manufacturing companies' performance**	0.766	0.041	0.000***	(0.818, 0.670)***	Supported
***H2*: I4.0 base technologies → Smart manufacturing practices**	0.697	0.039	0.000***	(0.746, 0.610)***	Supported
***H3*: Smart manufacturing practices → Smart capabilities development**	0.642	0.044	0.000***	(0.702, 0.552)***	Supported
***H4:* Smart capabilities development → Companies' resilience**	0.567	0.076	0.000***	(0.643, 0.299)***	Supported
***H5*: Companies' resilience → Manufacturing companies' performance**	-0.125	0.071	0.039*	(-0.108, -0.240)***	Supported

Notes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ (one-tailed); β = beta coefficient, SD = standard deviation, BCa CI = bias-corrected and accelerated confidence intervals.

3.4.5 Robustness checks

Several robustness checks were considered to ensure the main results were free from estimation bias. First, endogeneity bias was tested for using the Durban–Wu–Hausman test to ensure that the primary results were free of inverse causality, sample-selection bias, and omitted variables (ULLAH et al., 2021). Using the Stata 17.0 software, *p* values > 0.05 were found for each regression equation in these tests. Therefore, it was concluded that endogeneity bias does not threaten the results. Finally, possible non-linear (or quadratic) effects between variables were tested for to ensure no model specification errors (WHITTAKER; SCHUMACKER, 2022). Ramsey's regression specification error test (RESET) was used to detect this bias (WOOLDRIDGE, 2020). Again using Stata 17.0, *p* values > 0.05 were found for every possible quadratic relationship in the model. Therefore, it was concluded that the model is free from model specification errors.

3.5 DISCUSSION

3.5.1 Research findings and previous literature

Unlike previous studies that have proposed I4.0 as a solution to deal with times of crisis directly (e.g. JAVAID et al., 2020; KUMAR et al., 2020), these findings suggest and prove a whole sequence of structuring relationships (paths) that combine to enable manufacturing companies to overcome disruptions. "I4.0 base technologies" showed a significant positive correlation ($p < 0.05$; $\beta = 0.697$) with "smart manufacturing practices", which has a correlation ($p < 0.05$; $\beta = 0.642$) with "smart capabilities development", which mediates ($p < 0.05$; $\beta = 0.567$) "companies' resilience", which in turn mitigates ($p < 0.05$; $\beta = -0.125$) the deterioration of "manufacturing performance". This result supports the paper's proposition that base technologies such as IoT, the cloud, big data, and data analytics/AI underlie an I4.0 path that supports smart manufacturing practices, capabilities, and resilience. The I4.0 path involves a sequence of smart technology implementation, enabling smart manufacturing practices that provide opportunities for development of smart capabilities, aiming to meet rapid reconfiguration requirements in times of crisis. Therefore, this research validates the proposition, based on Kusiak et al. (2018), Frank et al. (2019), and Meindl et al. (2021), that the base technologies of I4.0 support several manufacturing applications and that there is a relational path between them. To the best of our knowledge, this study is the first to assess the relationships that create paths based on I4.0 implementation.

Furthermore, this research considers that I4.0 cannot be seen as the immediate and direct solution to unexpected disruptions. Instead, the central point is preparing the company's responsiveness through a "path against crisis", as previous studies have pointed out (e.g. IVANOV; DOLGUI, 2020; KRISTIANTO et al., 2017; SPIESKE; BIRKEL, 2021). Thus, these research findings demonstrate that responsiveness is better developed when supported by an I4.0 path. This path can help companies to build responsiveness and, consequently, short-term resilience based on rapid development of smart capabilities to address unexpected crises.

Our results also show that, through the I4.0 path, smart manufacturing deployment enables the rapid development of smart capabilities centered on establishing smart practices. This study thus provides empirical evidence for such an association and enhancement, thereby adding to the understanding of the deployment of "smart manufacturing practices". Through the PBV lens, "smart manufacturing practices" were defined as practices accessible via I4.0 implementation. Effective implementation of smart manufacturing practices enables companies to develop smart capabilities to quickly reconfigure intangible and tangle assets. For example, Gao et al.'s. (2021) study shows that flexible practices are critical to responsive manufacturing strategies in coping with VUCA (volatile, uncertain, complex, ambiguous) environments during times of crisis. At the same time, innovation, digitalization, and autonomous capabilities contribute to flexibility (BUENO et al., 2022). Accordingly, flexible supply-chain and manufacturing practices can enable an innovation process to overcome disturbance events. For example, the fashion industry started mass-producing protective masks during the COVID-19 pandemic (ZHAO; KIM, 2021). Companies mastering flexible practices were found to be better able to adjust the volume and mix of their production during periods of opening and closing due to COVID-19 lockdowns (RAJESH, 2021). Therefore, as in the previous examples, flexible smart practices enable an innovative reconfiguration (capabilities) of processes and products (volume/mix) and manufacturing systems (assets).

While several studies have focused on the direct impact that I4.0 has on performance (e.g. DALENOGARE et al., 2018) or on practices that lead to increased operational performance (e.g. TORTORELLA et al., 2019), this study shows that “I4.0 base technologies” and “smart manufacturing practices” help develop robustness, reliability, and responsiveness (resilience) through “smart capabilities development”. Therefore, smart capabilities support greater responsiveness; i.e., they leverage “companies’ resilience” (IBN-MOHAMMED et al., 2021; IVANOV, 2020; JANSSEN; VAN DER VOORT, 2020; PAPAGIANNIDIS et al., 2020; SIGALA, 2020). Resilience is the outcome of the I4.0 path (“I4.0 base technologies” → “smart manufacturing practices” → “smart capabilities development”) and mitigates the negative effects of the COVID-19 crisis on companies’ performance.

This research also uses the PBV to explain performance stability achieved through I4.0 path development and resilience. I4.0 is a set of technologies bought, researched, or developed (internally or externally) from manufacturing companies and partners aiming for performance improvements (DUMAN; AKDEMIR, 2021). This research, therefore, assumes that these technological adoption practices are imitable and increasingly disseminated by countries, sectoral associations, and universities. Therefore, according to the PBV, the variability in regular performance can be explained by the degree of adoption of imitable practices between companies in an industry (BROMILEY; RAU, 2014). Hence, through the PBV lens, manufacturing companies mastering smart practices and capabilities can achieve performance stability via resilience building.

Regarding performance stability, the research findings show that “companies’ resilience” mitigates the degradation effect on “manufacturing companies’ performance”. This finding means that when manufacturing companies adopt I4.0, triggering smart practices and capabilities, their responsiveness is improved, mitigating the degradation caused by disruptive external effects on companies’ performance (operational and financial). This can be explained by the fact that manufacturers with some degree of digitalization/integration/automation support better remote working, remote manufacturing control, virtualization, and autonomous operations (PAPADOPOULOS et al., 2020; PAPAGIANNIDIS et al., 2020). These companies are expected to show greater responsiveness (response capacity and agility), robustness (operations performance stability), and reliable operations during crisis management, such as the COVID-19 pandemic (IVANOV; DOLGUI 2020; JANSSEN; VAN DER VOORT, 2020; SHARMA et al., 2020; SIGALA, 2020).

Therefore, instead of addressing I4.0 only as a phenomenon capable of increasing operational productivity, as it was primarily addressed in the pre-pandemic period (e.g.

KAMBLE et al., 2019), the present study points out that I4.0 approaches can underpin an entire system of smart manufacturing, linking base technology antecedents and subsequent smart capabilities along a path. Companies mastering this path tend to be more resilient and better prepared to mitigate the effects of disruptions and times of crisis (RAJESH, 2021). The research findings suggest that companies with an advanced smart structure could develop resilience characteristics both in the long and short term, mitigating the effects of COVID-19 regarding operational and financial performance deterioration.

3.5.2 Theoretical contributions

In the I4.0 journey, establishment of smart manufacturing practices and development of smart capabilities are essential processes for manufacturing organizations to achieve expected benefits. Smart practices tend to be more impactful in times of crisis, since the I4.0 concept allows for a better understanding and attainment of manufacturing responsiveness, reliability, and robustness (PAPADOPOULOS et al., 2020; PAPAGIANNIDIS et al., 2020). Smart manufacturing enables flexible actions that support performance stability in production operations during sudden events, such as the COVID-19 crisis (RAJESH, 2021). I4.0 can leverage the outcomes of traditional operations, transforming them into smart operations (TORTORELLA et al., 2019). Owing to greater resilience, it is possible to maintain performance levels, even in times of crisis, by avoiding performance deterioration due to greater robustness, reliability, and responsiveness (JANSSEN; VAN DER VOORT, 2020; TORTORELLA et al., 2020). This study provides empirical evidence for such an association and enhancement, thereby adding to the understanding of I4.0 technologies' implementation and their effects in times of crisis.

Our findings provide another significant theoretical contribution in that a certain degree of flexibility and smart capabilities support robustness, reliability, and responsiveness concerning short-term manufacturing changes and help maintain short-term performance stability. This evidence is associated with positive effects between I4.0 and short-term performance stability during the COVID-19 crisis, as detailed in Sections 4 and 5.1.

Smart manufacturing practices support unique smart capabilities and mindsets that leverage performance improvements in manufacturing systems (BUER et al., 2018; MOEUF et al., 2018; TORTORELLA et al., 2019). From an analytical perspective, the technological and organizational changes brought about by I4.0 reinforce smart practices and capabilities, enabling: (i) the combining of competitive advantages; (ii) manufacturing companies to position themselves successfully; (iii) improved resilience in times of crisis; and (iv) short-term resilience based on development of smart capabilities (e.g. autonomy, real-time capabilities, servitization, adaptability, predictability, and big data-driven solutions).

There is undoubtedly an opportunity for manufacturing companies to properly balance the relevant trade-offs when introducing I4.0 smart technologies. However, manufacturing systems can also leverage transformative and innovative smart capabilities based on unique, adapted assets for the local smart manufacturing practices environment. Therefore, technology implementation does not necessarily lead to positive and immediate effects on performance; mastering this bundle of smart practices based on I4.0 technologies (through mastering dynamic capabilities) is required to fully affect performance (BROMILEY; RAU, 2016; TORTORELLA et al., 2019).

Our study also validates four I4.0 technologies (IoT, the cloud, big data and AI, and analytics), five smart manufacturing practices, three smart capabilities, ten types of manufacturing responses to four COVID-19 effects, and six performance indicators. This study shows that most of the original constructs and formative variables converge into one related bundle. The empirical validation of I4.0 base technologies that address smart manufacturing is consistent with the framework proposed by Frank et al. (2019).

In this context, this research provides empirical evidence for I4.0 technologies, however, this research proposes the assessment of smart practices in relation to responsiveness, reliability, and robustness requirements. Furthermore, the empirical validation of the relationship between smart capabilities and company performance is largely consistent with the frameworks proposed by Bueno et al. (2020) and Duman and Akdemir (2021).

Hence, responsiveness, reliability, and robustness could be considered resilience characteristics that are created via smart practices and capabilities, which help manufacturing companies overcome times of crisis. Responsiveness (agility and system flexibility), reliability (stability and continuity of operations), and robustness (reliability and responsiveness) provide a certain degree of resilience (IVANOV, 2020; IVANOV; DOLGUI, 2020; JANSSEN; VAN DER VOORT, 2020; RAJESH, 2021; SHEN et al., 2020). Notably, a link was found between performance stability during the COVID-19 crisis and resilience characteristics.

The insights from this study have also been examined from a PBV perspective, revealing that I4.0 implementation, such as digitalization and the infrastructure environment, the integration of systems, and the automation of factories, can influence the feasibility and performance of smart manufacturing in times of crisis. The study findings support the assumption that I4.0 adoption can have a distinct impact on consolidating smart manufacturing practices, which positively affects the development of smart capabilities. This research suggests that smart capabilities occur based on the smart manufacturing practices established according to each factory's specificities and environment, positively affecting performance. This study provides evidence from the Brazilian industrial sector. The phenomenon of I4.0 adoption also helps understand manufacturing companies' performance stability in volatile periods, such as the COVID-19 crisis, based on technological transition and innovation practices and capabilities. To the best of our knowledge, this is the first study to associate I4.0 technologies and their paths with the deployment of smart manufacturing practices, investigating manufacturing companies' resilience during the COVID-19 crisis.

3.5.3 Managerial implications

As manufacturers search for efficient production systems, smart technologies can boost their performance and innovativeness. Simultaneously, I4.0 initiatives can lead to agile actions to help governance within manufacturing companies in unpredictable scenarios, such as during the COVID-19 pandemic. However, its implementation entails enormous challenges for companies, especially in emerging economies. It is impossible to quickly implement complex, high-cost, and risk-contingent efforts such as I4.0. To achieve this, plans, strategies, and operational-organizational preparation are required. Therefore, this study provides manufacturing managers and practitioners with an indication of the appropriate path, based on adopting I4.0 technologies, smart manufacturing practices, and the associated competencies or capabilities for value creation, which constitutes a way to ensure companies' manufacturing performance stability.

Our results also have other practical implications. Suppose, for example, that a company's response to improve performance in times of crisis depends on the company's digital/smart structure. In this case, the development of resilience should also be a strategic target triggered by the I4.0 journey. Several studies have pointed out the benefits of I4.0 implementation, including manufacturing flexibility (KUMAR et al., 2020), increased product quality (AHMED et al., 2019), and increased manufacturing productivity (BUENO et al., 2020; DALENOGARE et al., 2018). However, there is a gap in the literature regarding responsiveness, reliability, and robustness (the 'triple R'), in relation to manufacturing disruptions, as a benefit of I4.0 implementation. In this context, the literature has discussed I4.0 investments and the consequences of technology acquisition; however, it has ignored the impact of unexpected high-risk situations, such as COVID-19, which could justify such investments to minimize performance deterioration, as opposed to increasing revenues. Hence, a risk analysis would be more appropriate than a conventional investment analysis, as the true value of digital transformation is evident in times of disruption. This study provides an initial perspective in this context, which deserves further evaluation in future studies.

Our research provides evidence to support managers' decision-making processes and sectoral policy guidelines: if they adopt many smart manufacturing practices related to responsiveness, reliability, and robustness (leading to resilience), this should also improve digitalization and servitization, manufacturing factory systems' integration (vertical, horizontal, end-to-end), and automation (autonomy, learning, knowledge, data-driven capabilities) to help achieve performance stability in times of crisis. With IoT, the cloud, big data, and data analytics in place, along with a smart manufacturing operating system, a manufacturing company can sustain performance standards in unpredictable and severe crisis periods. Overall, the study findings can help managers anticipate and deal with manufacturing difficulties by using smart technologies to adopt practices that create unique capabilities when times of crisis require rapid changes. This study helps set realistic expectations that can support managers' investment decisions to achieve performance stability during times of crisis, using smart manufacturing practices and competencies to endow companies with responsiveness, robustness, and resilience in times of crisis, such as COVID-19. Therefore, the findings of this study can contribute both to practice and theory, as highlighted below (Table 3.9).

Table 3.9 - Theory and practice contributions of the present research

Research gaps	Theoretical contributions	Practical implications
Research Gap 1: Test previous research theories about I4.0 approaches	To the best of our knowledge, the present study is the first to statistically prove that the I4.0 structure is composed of I4.0 base technologies, smart manufacturing practices, and smart capabilities development. Previous literature suggests this structure and the present research validates this proposition. This result represents a contribution to the evolution of the I4.0 literature. Additionally, this shows the necessity of the degree of I4.0 maturity in companies to provide capabilities that will contribute to the evolution of operations management.	The present research provides managers and engineers with paths for implementing I4.0. The need for maturity in the base technologies is evident for companies' development of smart practices and capabilities that will lead to superior operational results.
Research Gap 2: Lack of research empirically validating that Industry 4.0 adoption improves companies' resilience in times of COVID-19 crises.	The present research contributes to the evolution of the supply chain resilience literature when collecting data and validating a conceptual model at a unique moment in human history, during the breakdown of the global supply chain. Aspects of resilience must be built by companies over time; however, resilience is an ideal measurement construct during times of crisis, and the present study collected data and measured resilience at the height of the COVID-19 pandemic in one of the countries which experienced the greatest impact. The findings suggest that the I4.0 structure provides companies with resilience in face of a major disruption, thus contributing to the evolution of the resilience literature.	This research presents to engineers and managers the set of technologies, practices, and smart capabilities associated with developing resilience practices. Therefore, it provides a guide for managers who need to improve their company's resilience. Managers can focus on I4.0 aspects that have been scientifically proven to support resilience practices. Companies applying the conceptual model proposed in this research will be better prepared to face the challenges of a post-COVID-19 world and future crises.

Research gaps	Theoretical contributions	Practical implications
Research Gap 3: Lack of research empirically validating that companies' resilience improves their performance.	The present research contributes to the literature when the findings suggest that companies which are adept at I4.0 were more resilient to the COVID-19 pandemic and maintained stability in operational performance indicators in the face of major disruption. The positive relationship between resilience and performance was reported in the previous literature; however, the present study contributes by measuring this relationship at a unique moment in history, during the COVID-19 outbreak.	The conceptual model validity demonstrated in the present study could guide managers and engineers in I4.0 implementation. Thus, managers can guarantee the company's robustness in times of crisis and keep operational performance indicators stable. Therefore, this study helps companies to be prepared to face future crises.

3.6 CONCLUSIONS

The COVID-19 pandemic led to social changes and severe effects on operations, with many countries enforcing lockdowns, which entailed losses for supply chain and manufacturing companies in various economic sectors (MOTA et al., 2022; VERMA; GUSTAFSSON, 2020). This study’s main purpose was to investigate an I4.0 path dealing with the effects of the disruptive crisis entailed by the COVID-19 pandemic on manufacturing companies’ performance. For this purpose, six constructs were verified empirically: COVID-19’s effects (COV); I4.0 base technologies’ implementation (IBT); establishment of smart manufacturing practices (SMP); development of unique smart capabilities (SCD); companies’ resilience-building characteristics (CRS); and manufacturing companies’ performance deterioration (MCP).

Our findings show that companies’ operational responses based on the I4.0 approach helped manufacturers to maintain their performance during the COVID-19 crisis. Therefore, this study’s findings empirically validate an I4.0 implementation path, as proposed by Frank et al. (2019) and Meindl et al. (2021). This research shows that I4.0 supports the development of resilience characteristics, i.e. flexibility, reliability, robustness, and responsiveness (KRISTIANTO et al., 2017). The survey findings also demonstrate that, in line with Frank et al. (2019) and Kusiak et al. (2018), smart manufacturing practices provide manufacturing companies with performance stability during times of crisis. It is possible that the positive effects of developing unique smart capabilities (BUENO et al. 2020, BAG et al. 2021) on resilience can mitigate the negative impacts of the COVID-19 crisis on performance.

This research found that manufacturing companies’ resilience characteristics mitigate short-term performance degradation caused by the COVID-19 crisis. Furthermore, specific response measures tend to reduce the effects of this crisis when influenced by manufacturing companies' resilience-related characteristics. In addition, such responses may also positively influence these organizations' chances of survival when facing future crises.

3.6.1 Limitations and suggestions for future research

Although several countermeasures have been addressed, this study has some limitations that need to be discussed. First, the sample has certain limitations. Although the sample was sufficient to prove that the COVID-19 pandemic has harmed manufacturing companies and that smart manufacturing practices help organizations overcome the effects of COVID-19, it is necessary to develop and empirically test the model with larger samples. Increasing the sample by replicating the study in different countries would support greater generalisability.

Our questionnaire addressed information from different industrial sectors and organizational levels. However, some information is only shared with senior managers in organizations, so in some cases, the data are based on respondents' (e.g. analysts') global views of the organization in which they work. Therefore, this research suggests that data should be collected only from managers or directors in future studies. Furthermore, this research covered industries from different sectors. For future research, it is suggested to focus on a specific manufacturing industry, because the effects of the COVID-19 pandemic may have had a different intensity depending on each company's market.

Companies' different experiences in adopting I4.0 technologies also represent a limitation, possibly influencing respondents' perceptions of implementing smart manufacturing practices. For Brazilian companies, I4.0 is still a recent approach. Therefore, this research encourages the replication of this research in developed economies, among companies with advanced implementation of I4.0 technologies. Additionally, a comparative study of companies at the same stage of I4.0 technology adoption in other developing countries could avoid any potential errors in the collected data. Future research should be developed to assess the effect of the COVID-19 pandemic on companies that have adopted lean manufacturing, Six Sigma, or sustainable approaches. Research that addresses companies' responses in the face of the COVID-19 pandemic by integrating different management approaches could contribute to the advancement of responsiveness/resilience in operations management.

A more in-depth study of the COVID-19 pandemic's effects and the challenges companies will face in a post-COVID-19 world is also suggested. This research encourages longitudinal studies to identify new impacts of the COVID-19 pandemic for companies, or studies that involve front-line supervisors in rating the effects of COVID-19 and the implementation of smart manufacturing practices. New variables/constructs could be included in such analysis, or multiple levels of analysis could be used to observe the influence of COVID-19 over time. Further, in-depth case studies addressing measures taken by companies during the COVID-19 pandemic may provide a better understanding of how companies should act in a post-COVID-19 world and how they should face future pandemics or crisis events.

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APPENDIX A. RESEARCH QUESTIONNAIRE

1. Please, answer the following information with respect to the company you work for:

(a) Company name´s (optional): ___________ e-mail (optional): ___________

(b) Industry sector:

(c) Company size:___________employees

(d) Working time (months/years) in the company: ___________years

(e) Time of Industry 4.0 technologies implementation in the company: ___________ years

(f) Your experience with Industry 4.0 technologies implementation: ___________ years

(g) Your job title within your company:

( ) Engineer or Analyst

( ) Supervisor or Coordinator

( ) Manager or Director

( ) CEO or Owner

( ) Other:___________

(h) Markets attended by the company:

( ) Metal products	( ) Pulp and Cellulose	( ) Software and Technology
( ) Pharmaceutical	( ) Agriculture	( ) Energy
( ) Biotechnology	( ) Mining	( ) Tobacco
( ) Leather-footwear	( ) Petrochemicals	( ) Furniture
( ) Food and drinks	( ) Chemicals	( ) Electrical/Electronic
( ) Steelworks	( ) Transport	( ) Meat

( ) Others: ___________

(i) Please, indicate which category do you perceive your company regarding the adoption and/or development of innovations for Industry 4.0:

( ) Innovators ( ) Early adopters ( ) Early majority ( ) Late majority ( ) Laggards

2. Please, indicate the degree of interest that your company has in Industry 4.0 technologies:

( ) We are not interested in Industry 4.0

Could you tell us why?____

( ) We are interested, but we do not know the concepts of Industry 4.0 well

( ) We are interested and updated on the concepts of Industry 4.0

( ) We are interested in and have already developed some pilot projects for the implementation of industry 4.0 technologies

( ) We have fully engaged with concrete investments in industry 4.0 technologies

3. Please, regarding the company's performance since March 2020, you could indicate your level of the agreement on the following:

** Scale: from 1 (fully disagree) to 7 (fully agree)*

3.1 Productivity in our company has been affected negatively by the COVID -19 pandemic

3.2 The quality of our product has been negatively affected by the COVID-19 pandemic

3.3 Waste in our company increased in the period mentioned

3.4 Our company’s financial performance has been affected negatively by the COVID-19 pandemic

3.5 The overall performance of our company has been affected directly by the economy’s “open/close”

3.6 Our company's capacity availability was negatively affected by the COVID-19 pandemic

3.7 The defect rate of our products increased during the COVID-19 pandemic

3.8 The delay in delivering our orders increased during the COVID-19 pandemic

3.9 The time elapsed from the customer’s order until the customer received it (lead time) worsened during the COVID-19 pandemic

3.10 We had raw materials’ shortage during the COVID-19 pandemic

3.11. Finished product inventory levels decreased during the COVID-19 pandemic

4. Please, indicate below the degree of development of the technological bases that make Industry 4.0 feasible in your company:

** Scale: from 1 (not used) to 7 (fully adopted)*

4.1 Internet of Things

4.2 Cloud (e.g. data stored in the cloud)

4.3 Big data

4.4 Data analytics

5. Indicate the implementation degree for smart manufacturing technologies/solutions in your company (Vertical integration):

** Scale: from 1 (not used) to 7 (fully adopted)*

5.1 Regulatory process control (e.g., sensors, actuators, PLCs)

5.2 Process monitoring, control, and supervision (SCADA)

5.3 Production planning and control systems integrated with equipment (MES)

5.4 Business process management systems integrated with manufacturing systems (e.g., ERP)

5.5 Virtual commissioning for automation systems (e.g., PLCs)*

*Note: By using the virtual commissioning solutions, the PLC codes can be debugged in a virtual environment before downloading them on the actual equipment. By simulating and validating the automation equipment virtually, it is possible to confirm that it will work as expected.

5.6 Communication and integration between machines (M2M)

5.7 Artificial intelligence for predictive diagnostics in equipment

5.8 Artificial intelligence for production planning and control (e.g., Big data analytics, Data mining, Machine Learning, etc.

5.9 Process simulation to aid decision-making (e.g., digital manufacturing)*

*Note: In the concept of digital manufacturing, data management systems and simulation technologies are used together to optimize manufacturing before starting production and supporting the ramp-up phases.

5.10 Automatic identification of non-conformities in production

6. Indicate the degree of implementation of Smart manufacturing technologies/solutions in your company - Internal Traceability:

** Scale: from 1 (not used) to 7 (fully adopted)*

6.1 Raw material identification and traceability

6.2 Identification and traceability of components of final products

7. Indicate the degree of implementation of Smart manufacturing technologies/solutions in your company - Production system autonomy:

** Scale: from 1 (not used) to 7 (fully adopted)*

7.1 Industrial robotic systems

7.2 Collaborative man/machine work (collaborative robots)

8. Indicate the degree of implementation of Smart manufacturing technologies/solutions in your company – Energy efficiency:

8.1 Energy efficiency monitoring system

8.2 Energy efficiency improvement system

9. Indicate the degree of implementation of Smart manufacturing technologies/solutions in your company – Flexibility and Customization:

** Scale: from 1 (not used) to 7 (fully adopted)*

9.1 Additive manufacturing (production line with 3D-printers)

9.2 Flexible and autonomous production lines

10. Considering the impacts the COVID-19 outbreak had on your organization/supply chain, please, indicate your level of agreement:

** Scale: from 1 (fully disagree) to 7 (fully agree)*

10.1 Our industry/sector was strongly affected by the COVID-19 outbreak

10.2 Our company was strongly affected by the COVID-19 outbreak

10.3 Our suppliers were strongly affected by the COVID-19 outbreak

10.4 Our competitors were strongly affected by the COVID-19 outbreak

10.5 Our demand was strongly affected by the COVID-19 outbreak

10.6 Our factory interrupted its operations during the pandemic

11. Considering measures taken by your company in response to the crisis caused by the COVID-19 outbreak, please, indicate your level of agreement:

** Scale: from 1 (fully disagree) to 7 (fully agree)*

11.1 We managed to deal with the sudden disruption of suppliers

11.2 Our suppliers were able to fulfill our requirements/orders

11.3 We have not had any significant delays in delivering our products

11.4 We managed to deal with the sudden change in demand for our products

11.5 We were able to provide health, safety, and hygiene to our employees and customers

11.6 We were able to remotely working when it was required

11.7 We had no capacity restrictions on the production

11.8 We can deal with physical distribution problems caused by the COVID-19 pandemic

11.9 We were able to deal with financial constraints caused by the COVID-19 pandemic

11.10 Our company created a crisis management committee to deal with the effects of COVID-19

11.11 Our organization has been responsive and flexible during the COVID-19 pandemic 11.12 Our organization employed digital technologies in its operations to overcome COVID-19 pandemic challenges
11.13 Our policy of continually seeking to reduce waste has helped us to overcome the challenges of the pandemic
11.14 Our organization has a risk management system in the supply chain as a way to mitigate the effects of COVID-19 pandemic
11.15 Our organization was able to handle deliveries "without touch/contact"

12. Considering the effects of the introduction of Industry 4.0 technologies in your company, please indicate your agreement level to the following statements: (Capabilities)

**Scale: from 1 (fully disagree) to 7 (fully agree)*

(a) Our company makes efforts to promote coordination/integration in our internal processes, manufacturing, information, and management systems

(b) Our company makes efforts to develop/adopt integration processes of our supply chain operations supplies, distribution, and management systems customers

(c) Our company makes efforts to develop/adopt a wide range of innovative products and processes

(d) Our company makes efforts to develop/adopt a wide range of innovative technologies in real-time to visibility, traceability, and monitoring of resources and equipment

(e) Our company makes efforts to develop/adopt a high level of automation for production and autonomy for manufacturing machines and systems

(f) Our company makes efforts to digitalize data collection data and connectivity infrastructure from the factory to the most operational and information processes

(g) Our company makes efforts to develop/adopt a high connectivity infrastructure between field, machines, operating systems, information, and people

(h) Our company makes efforts to develop/adopt a high level of automation and autonomy for the process of decision: a collection of big data / big data, information extracted from big data/machine learning and data analytics, and decision making with artificial intelligence tools)

(i) Our company makes efforts to develop/adopt operational and managerial processes-as-a-service (e.g., an ERP module offered in a cloud)

(j) Our company has a digital culture and familiarity with industry 4.0 technologies at all levels of employees (from top management to the shop floor)

13. Would you like to leave any final comments or observations?

Notes:____

CHAPTER 4 FROM GENERAL TRENDS TO SPECIFIC ADAPTATIONS: A COMPLEX ADAPTIVE SYSTEMS (CAS) APPROACH TO RESILIENCE IN OPERATIONS MANAGEMENT

Abstract: The coronavirus disease 2019 (COVID-19) was characterized as a pandemic that performs as a transboundary crisis with an exponential growth rate. In the face of a "flattening contagion curve", social distancing has become part of a daily lifestyle for individuals, governments, and companies. Thus, companies needed to adapt their production system to maintain productivity and avoid collapse. This paper aims to present the emerging topics in literature during the pandemic and insights into the legacy of COVID-19 for operations management. To achieve this goal a systematic literature review (SLR), expert validations, and semi-structured interviews with aeronautical industry practitioners were carried out. The study’s main outcome is the discussion of 17 emerging themes amid the COVID-19 pandemic, providing an elucidation of management approaches that have demonstrated both efficacy and insufficiency in responding to major disruptions. The discuss of results is based on Complex Adaptive Systems (CAS) theory. The main findings of our research are the consolidation of remote work as a reality for most operations in a post-COVID-19 world; Lean Manufacturing and Industry 4.0 have been established as approaches aligned with resilience; digital transformation has become a reality for companies; significant changes in business models have occurred; and innovation and agile strategies have enabled organizations to adapt to sudden market demands. To the best of our knowledge, this is the first study focusing on the legacy of COVID-19 on operations management with insight from the aeronautical industry. So we encourage new research with insights for other industries to improve the literature about the legacy of COVID-19 in operations management. As for the practical implications, our study will be a guide for organizations to become more resilient when facing future pandemics or disruptions.

Keywords: CONVID-19 legacy; systematic literature review, aeronautical industry.

4.1 INTRODUCTION

The history is punctuated by wars, natural disasters, and pandemics, underscoring the uncertainty of the future amidst the major and minor disruptive events happening worldwide. The recent incursion by Russia into Ukrainian territory in 2022 has reverberated politically and economically on a global scale. Furthermore, in 2023, the terrorist group Hamas attacked Israel to reclaim territories, further unsettling global politics and fostering an environment of uncertainty. The COVID-19 pandemic, originating in 2019 from viral spread, continues to persist, albeit in a mitigated form due to widespread vaccination efforts. It is still too early to see the social, technological, and operational transformations stemming from these recent events. Still, we are navigating an era characterized by disruptions, challenges, and opportunities for learning. Then, amidst crises institutional changes challenging the status quo possible (GUNASEKARAN; NGAI, 2012).

The COVID-19 pandemic has highlighted companies' need to develop resilience in unprecedented disruptions. Characterized by its transboundary nature and exponential spread, the pandemic forced organizations worldwide to rapidly adapt their operations to maintain productivity and avoid collapse (BRYCE et al., 2020; WHO, 2023; BOIN, 2019). In response to efforts to 'flatten the contagion curve,' social distancing has become a daily practice for individuals, governments, communities, industrial firms, and academic institutions (SARKIS et al., 2020). This paper explores how companies can leverage theories of Complex Adaptive Systems (CAS) and resilience to navigate such major events effectively.

CAS theory provides a robust framework for understanding how organizations, viewed as complex systems, adapt, and evolve in response to significant changes. The CAS perspective emphasizes several key features crucial for understanding and enhancing organizational resilience including adaptation and coevolution, non-linearity, self-organization, emergence, ability to learn, and schema. These features collectively highlight the complex interactions and adaptive capacities necessary for organizations to thrive amid disruptions (TUKAMUHABWA et al., 2015).

Ali et al. (2017) outline three phases of disruption: pre-disruption, during-disruption, and post-disruption. They also identify five critical capabilities for supply chains: anticipation, adaptation, response, recovery, and learning. Examining the COVID-19 crisis, operations management is currently facing challenges in the post-disruption phase, and developing their learning capability. The post-COVID-19 phase and the development of learning capabilities are crucial for shaping the future of operations management. However, such learning often lacks specificity, ignoring the particularities of different sectors. This paper argues that understanding sector-specific adaptations is crucial for comprehensively grasping how companies can build resilience. To achieve this, we will conduct a systematic literature review (SLR) to identify general trends in operations management during the COVID-19 pandemic. These findings are validated through expert opinions. We will highlight 17 emerging themes encapsulating the management approaches adopted during the pandemic.

Next, we will conduct a structured interview with experts from the aeronautical sector to illustrate how these general topics were addressed in a specific sector. This example will demonstrate how sector-specific characteristics influence adaptation and resilience. We argue that to be prepared for the next wave of disruptions, companies should incorporate both general strategies and schemas as well as specific sector characteristics into their resilience planning. By doing so, they can enhance their ability to anticipate, adapt, respond, recover, and learn, thus becoming more resilient in the face of future challenges.

In sum, our study advocates for a combined approach that considers both general trends and sector-specific adaptations. The practical implications of our findings offer a guide for organizations seeking to enhance their resilience in the face of future disruptions.

The remainder of this article is structured as follows. Section 2 consolidates the theoretical background. Section 3 describes the methodology research, whose findings are presented and discussed in section 4. Finally, section 5 presents a conclusion, research limitations, and future study suggestions.

4.2 THEORETICAL BACKGROUND

4.2.1 Supply Chain Resilience (SCRES)

The earliest definitions of SCRE emerged in the early 2000s (e.g., RICE; CANIATO, 2003; CHRISTOPHER; PECK, 2004). However, prior to that, Holling (1973), a pioneering researcher in resilience, defined resilience as the persistence of systems and their ability to absorb change and disturbance while maintaining the same relationships between variables. According to Christopher and Peck (2004), resilience is the ability of a system to return to its original state or transition to a more desirable state after being disturbed. This definition highlights flexibility and the importance of adaptability, as the desired state may differ from the original. The authors pointed out that resilience encompasses flexibility and agility, affecting not only process redesign but also fundamental decisions on sourcing and fostering more collaborative supply chain relationships through greater transparency of information.

Tukamuhabwa et al. (2015) conducted a systematic literature review to propose a definition of SCRES based on key elements found in the existing literature. They define SCRES as the adaptive capability of a supply chain to prepare for and respond to disruptions, enabling timely and cost-effective recovery, and ultimately progressing to a post-disruption state of operations—ideally, an improved state compared to before the disruption. Besides, Chowdhury and Quaddus (2017) argue that to build resilience, the supply chains need both proactive and reactive capabilities to adapt, integrate, and reconfigure during the pre-disaster and post-disaster phases surrounding disruptive events.

The COVID-19 pandemic has underscored the critical importance of supply chain resilience, prompting extensive research on how supply chains can better prepare for, respond to, and recover from disruptions. During the crises the resilience has been studied in different aspects, there are studies about the role of supply chain risk management (SCRM) in mitigating COVID-19 effects on SCRE (BAZ; RUE, 2020; MARZANTOWICZ; NOWICKA; JEDLIŃSKI, 2020), about the lack of resilience in the food and beverage supply chain (CHENARIDES; MANFREDO; RICHARDS, 2021; CHOWDHURY et al., 2020; REJEB A.; REJEB K.; KEOGH, 2020), about the agility, resilience and sustainability perspectives integration during the COVID-19 pandemic (IVANOV, 2020b); the ripple effect of the COVID-19 outbreak in global SCs (IVANOV and DAS, 2020; IVANOV; DOLGUI, 2020c); viability in SCRE in times of COVID-19 crises (IVANOV; DOLGUI, 2020a); about digital supply chain twin for managing the disruption risks and resilience in COVID-19 times (IVANOV; DOLGUI, 2020b); about essential factors, barriers and enables which can help companies to overcome COVID-19 crisis and help companies to be resilient (KHURANA et al.2021; OKORIE et al., 2020); the importance of resilience, strategic agility, and entrepreneurship in the context of the fight against COVID-19 (LIU; M. LEE; C. LEE, 2020). The previous research highlighted that companies can enhance their resilience, ensuring continuity and even operations improvement in the face of future disruptions.

4.2.2 Complex Adaptive Systems (CAS) theory lens for SCRES research

Tukamuhabwa et al. (2015) propose the Complex Adaptive Systems (CAS) theory as an appropriate lens for studying SCRES. The authors illustrate that SCRES exhibits many characteristics of a CAS. Pathak et al. (2007a) define a Complex Adaptive Supply Network (CASN) as a system of interconnected autonomous entities that make choices to survive and, collectively, evolve and self-organize over time. A CASN consists of four key elements: organizational entities exhibiting adaptability, a topology with interconnectivity between multiple supply chains, self-organizing and emergent system performance, and an external environment that coevolves with the system. The fundamental concept of a supply network is a group of firms engaged in activities to fulfill customer requirements. While these firms share a common global goal, there are typically different levels of rewards allocated to each member of the supply network. Since each member is an autonomous unit, they make independent decisions to maximize their local goals (PATHAK et al., 2007b).

Tukamuhabwa et al. (2015) systematically reviewed the literature to demonstrate the connections between CAS and SCRES. Their findings reveal that SCRES exhibits key characteristics of CAS, including adaptation and coevolution, non-linearity, self-organization, emergence, ability to learn, and schema. The authors define these connections as follows: firms adapt to supply chain threats, causing further environmental changes (adaptation and coevolution); non-linearity and interdependence mean small disturbances can lead to significant threats, making strategies like increasing visibility and flexibility through multiple sourcing crucial for survival; resilience is an emergent feature resulting from self-organized processes that enhance adaptation, with no single firm controlling the entire supply chain's resilience; gents in a CAS learn by gathering information from their interactions within the system and the surrounding environment, and schemas encompass strategies and plans, such as firms' supply chain resilience strategies, which enable them to modify operations and adapt to supply chain threats.

A CASN perspective is employed to interpret existing literature on disaster relief efforts, highlighting how relief organizations, their interactions, and their environmental context influence the resilience of supply networks following disasters. CASN helps explain why conventional supply chain management practices yield varying outcomes in disaster relief. Resilience in supply networks can be enhanced through managerial decisions and policy revisions by influencing factors such as clustering and connectivity, path length and redundancy, topology dynamics, and trust within distributed networks. (DAY, 2014).

4.3 RESEARCH METHODOLOGY

To achieve the objectives of the present study, exploratory research with a qualitative approach was carried out. Pizzinatto and Farah (2012) affirm that qualitative research obtaining in-depth non-quantitative data on a given topic of interest. There is no intention of using statistical procedures for results analysis. As for exploratory research, Gil (2002), determines that the main objective is the improvement of ideas or discovery of intuitions, in a flexible way, which allows the consideration of the most variable aspects related to the studied fact.

4.3.1 Systematic Literature Review (SLR) and content analysis

According to Rowley and Slack (2004), to perform a literature review, it is first necessary to research several documents and establish similarities among them, which will provide guidance as to what should be included in the literature review. Then, notes should be made on the topics and also on the references that will be used in the study. Therefore, it is necessary to structure the literature review, identify the main themes, and organize the concepts and documents according to the research themes. In this way, it is possible to write the literature review, separating the relevant subjects into different sections. Finally, the bibliography of the study must be made, in which all articles used in the literature review must be cited and referenced.

The SLR developed for this study followed the steps determined by Denyer and Tranfield (2009). In the first step, the review planning (elaborating the research questions, inclusion/exclusion standards, and protocol) was performed. In the second step, the literature review was conducted (by defining the keywords and strings and selecting articles from databases). In the third step, the classification and analysis of the articles were performed. The content analysis was built using the NVivo 12 Plus software which allows for the efficient organization and storage of data. Moreover, the software enables the identification of complex relationships among the variables to enrich the results and provide reliable research (NVivo, 2019).

The literature review was conducted to find the emerging themes amid the COVID-19 pandemic, providing an elucidation about the legacy of COVID-19 to operations management. The search was performed using the Scopus, Web of Science, and Engineering Village databases. A research question was formed to guide the identification of the keywords and the construction of the research strings (Table 4.1).

A total of “2909” papers were obtained by applying the strings in Table 1. After removing the duplicate papers, “2043” papers were screened to titles and abstracts reading (filter 1). For the reading of the introduction and conclusion (Filter 2), 218 papers were selected. After checking the quality, accessing the work, and reading the introduction and conclusion 91 papers were selected for full-text review. Finally, a total of 91 papers were selected for the final classification (Figure 4.1). The filters used are shown in Table 4.2.

This systematic has identified 91 papers that address the COVID-19 outbreak on OSCM, as shown in Appendix A. Appendix A also presents information such as the year of publication, the site of publication, and the main contribution of the paper. For this research, there was a time constraint, so we searched for papers published after 2019 (the onset year of the COVID-19 pandemic.). The wide variety of publication sources shows that the theme is multidisciplinary and that it has increasingly attracted research communities.

Figure 4.1 – SLR filters

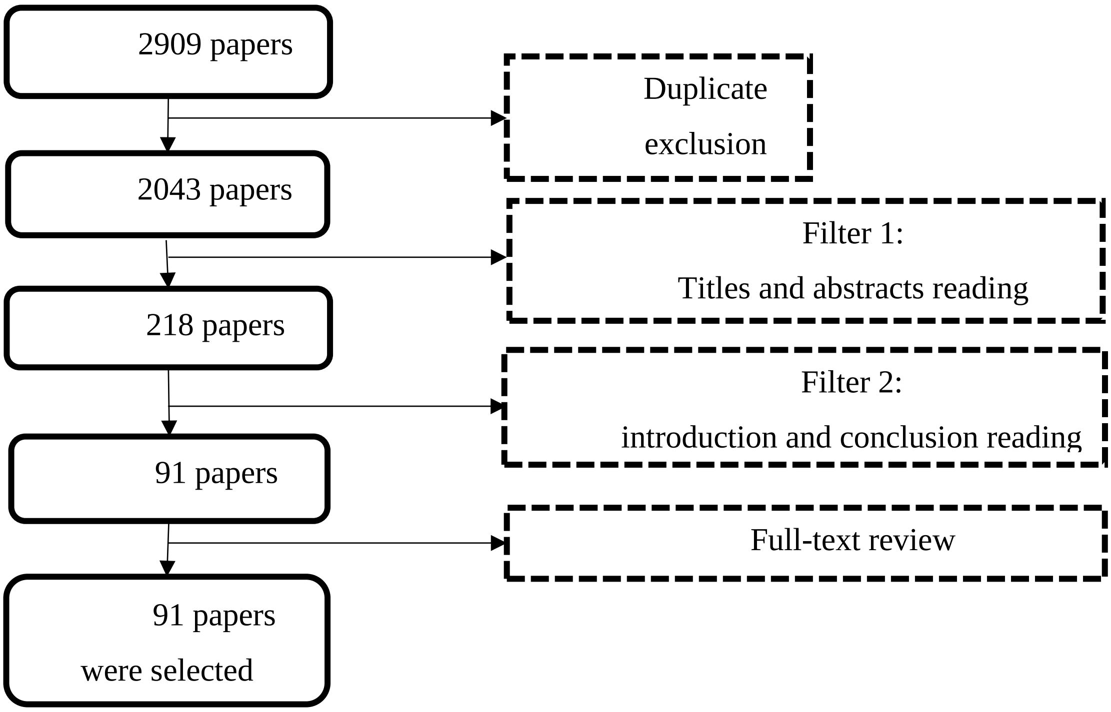

Table 4.1 – Research question, keywords, and research strings

<table>
<tr><th>Research question</th><th>keywords</th></tr>
<tr><td>1. What was the legacy of COVID-19 to operations management?</td><td>SARS-CoV-2; COVID; COVID-19; COVID-19 outbreak; COVID-19 crisis; coronavirus; pandemic; COVID-19 pandemic; global pandemic; global disruption; coronavirus-driven; epidemic outbreak; times of crisis; crisis; health crises; transboundary crisis;

Operations and Supply Chain Management; OSCM; Supply Chain Management; SCM; Operations Management; supply chain; supply networks; risk management; industry;

Lean production; Lean manufacturing; Lean thinking; Lean culture; Lean practices; Lean methodology; just-in-time; Industry 4.0; fourth industrial revolution; technological advancement</td></tr>
<tr><th colspan="2">String Scopus</th></tr>
<tr><td colspan="2">(TITLE-ABS-KEY ("SARS-CoV-2" OR covid OR "COVID-19" OR "COVID-19 outbreak" OR "COVID-19 crisis" OR coronavirus OR pandemic OR "COVID-19 pandemic" OR "global pandemic" OR "global disruption" OR "coronavirus-driven" OR "epidemic outbreak" OR "health crisis") AND TITLE-ABS-KEY ("Operations and Supply Chain Management" OR "OSCM" OR "Supply Chain Management" OR "SCM" OR "Operations Management" OR "supply chain" OR "supply networks" OR "risk management" OR "industry") OR TITLE-ABS-KEY (effect OR impact OR measures OR consequences OR lessons OR strategy OR quarantines OR "border closures" OR shutdown OR lockdown OR social AND distancing OR "behavioral changes" OR bankruptcy OR issues OR barriers OR difficulties OR challenges OR weaknesses))</td></tr>
<tr><th colspan="2">String Web of Science</th></tr>
<tr><td colspan="2">("SARS-CoV-2" OR covid OR "COVID-19" OR "COVID-19 outbreak" OR "COVID-19 crisis" OR coronavirus OR pandemic OR "COVID-19 pandemic" OR "global pandemic" OR "global disruption" OR "coronavirus-driven" OR "epidemic outbreak" OR "health crisis") AND TOPIC: ("Operations and Supply Chain Management" OR "OSCM" OR "Supply Chain Management" OR "SCM" OR "Operations Management" OR "supply chain" OR "supply networks" OR "risk management" OR "industry") AND TOPIC: (effect OR impact OR measures OR consequences OR lessons OR strategy OR quarantines OR "border closures" OR shutdown OR lockdown OR social AND distancing OR "behavioral changes" OR bankruptcy OR issues OR barriers OR difficulties OR challenges OR weaknesses)</td></tr>
<tr><th colspan="2">String Engineering Village</th></tr>
<tr><td colspan="2">((("SARS-CoV-2" OR covid OR "COVID-19" OR "COVID-19 outbreak" OR "COVID-19 crisis" OR coronavirus OR pandemic OR "COVID-19 pandemic" OR "global pandemic" OR "global disruption" OR "coronavirus-driven" OR "epidemic outbreak" OR "health crisis") WN KY) AND (("Operations and Supply Chain Management" OR "OSCM" OR "Supply Chain Management" OR "SCM" OR "Operations Management" OR "supply chain" OR "supply networks" OR "risk management" OR "industry") WN ALL))</td></tr>
</table>

Table 4.2 - Inclusion and exclusion criterion

Filter	Criterion	Inclusion	Exclusion
1	Focus	Papers whose main focus is the COVID-19 outbreak on OSCM. Papers that have been published since 2019.	Papers that do not refer to the COVID-19 outbreak on OSCM. Papers that address other pandemics, and papers that do not mention the COVID-19 outbreak. Papers that were published before 2019.
		Papers about the effects of the COVID-19 outbreak on the supply chain; papers that report future challenges for the post-COVID-19 world; papers that report the lessons left by the COVID-19 outbreak; papers that report such as Lean Manufacturing, Industry 4.0, or sustainable approaches can mitigate the COVID-19 effects on the supply chain.	Papers that only mention the COVID-19 outbreak, but do not focus on the COVID-19 outbreak. Papers that approach COVID-19 superficially, without reporting the effects for OSCM or the organizational challenges for a post-COVID-19 world. Papers that do not show the relationship between management approaches and the COVID-19 crisis.
Filter	**Criterion**	**Inclusion**	**Exclusion**
2	Access	Have access to the work and the work being written in English.	Not having access to the work and the work not being written in English.
	Quality	Scientific journals and international congresses.	Books and websites
	Analysis Unit	Papers that address the COVID-19 outbreak on OSCM. Papers that address the COVID-19 outbreak in organizations. Papers that address the COVID-19 outbreak in any industry sector. Papers that report theoretically or empirically the COVID-19 effects and challenges. Papers that show theoretically or empirically how an organization can benefit from approaches such as Lean Manufacturing, Industry 4.0, or sustainability to face the COVID-19 crisis. Papers that report the negative aspects of management approaches during the COVID-19 crisis.	Papers that address COVID-19 concerning people's health, medicines, vaccines, agriculture, tourism, the hotel industry, development of specific technologies, and political government issues. Papers that address other crises such as the Black Death, and Spanish flu, among others.

4.3.2 Validation conducted by experts on emerging topics during the pandemic

The research method used includes experts' participation to consolidate and refine the emerging topics during the pandemic from the SLR. To refine the emerging topics, we used the requirements suggested by Lewis (1998), Silveira et al. (2017), and Bianco et al. (2023a). Thus, two research requirements were defined to generate a meaningful and clear set of guidelines:

(i) the proper selection of experienced experts; and (ii) a systematic procedure for collecting, analysing, and synthesising the data from the SLR.

Four academic experts with broad experience in operations management were consulted. After each interview, the emerging topics were rephrased according to their suggestions. The meetings lasted an average of two hours. The collected data was registered, and the topics were consolidated after every meeting while the information was still fresh to the researcher. Thus, the iterative refinement process followed these steps (Silveira et al, 2017; Bianco et al., 2023a):

1. Analysis of the original version of the COVID-19 emerging topics in operations management;

3. Analysis of the latest version of the COVID-19 emerging topics in operations management as defined/refined by experts; and

4. The COVID-19 emerging topics in operations management are updated with the experts' new suggestions

4.3.3 Semi-structured interviews with aeronautical industry practitioners

Intending to complement the SLR, expert's validation, and understand the legacy of COVID-19 to operations management, we carried out semi-structured interviews with 17 aeronautical industry practitioners. The COVID-19 emerging topics in operations management were a guide to the interviews. During the interviews, we allowed the practitioners to discuss the legacy of COVID-19 within their sector of operations. The emerging themes in the literature broadly encompass operations management. Some of the themes identified in the SLR were corroborated by the interviewees; however, others were not seen as particularly relevant to the aeronautical industry. The interviews took place between March and April 2024. They were conducted by a researcher who relied on a research protocol with open-ended questions, as suggested by Yin (2003). Each interview was recorded and transcribed verbatim. Overall, we collected qualitative material for about 20 hours. The content analysis was built using the NVivo 12 Plus software. The aeronautical industry faced a major breakdown during the COVID-19 pandemic. Social isolation led to halted flights and decreased demand for commercial flights, which impacted the sector's economy, from airlines to aircraft manufacturers. Insights from practitioners in this sector are highly valuable for this research's focus. Further details about the interviewees can be found in Table 4.3.

Table 4.3 – Profile of the interviewees

Expert	Years of experience in the aerospace sector	Expert's area of activity
A	14 years	Process development engineering
B	10 years	Control and automation engineering
C	12 years	Aircraft maintenance management
D	17 years	Control and automation engineering
E	22 years	Process development engineering
F	23 years	Corporate information technology
G	22 years	Production management
H	14 years	Operational execution
I	20 years	Product development
J	22 years	Engineering in the Brazilian Air Force
K	22 years	Systems engineering
L	4 years	Product development engineering
M	38 years	Aircraft test pilot
N	11 years	Aircraft maintenance and flight readiness
O	22 Years	Business excellence
P	5 Years	Product development engineering
Q	9 years	Sustainability

4.4 RESULTS AND DISCUSSIONS

The legacy of COVID-19 on operations management is discussed in this section across six key aspects: technology aspects, supply chain management aspects, business model aspects, innovation aspects, continuous improvement aspects, and sustainability aspects. In this way, the discussion is based on emerging themes in the literature and insights from practitioners in the aeronautical industry.

4.4.1 Systematic Literature Review (SLR) and content analysis results

The SLR and content analysis results in emerging topics in the literature about the COVID-19 pandemic and OSCM. This topic was classified is 6 key aspects which are presented in Table 4.4. These topics were validated by experts and guided the interview with aeronautical industry practitioners.

Table 4.4 – Emerging topics in the literature of OSCM

Aspects of OSCM transformations	Emerging topics in the literature of OSCM
Technology aspect	1. Industry 4.0 technologies have demonstrated their efficacy in enhancing supply chain management by facilitating the transformation of traditional supply chains into digital supply networks (DSNs). (32 papers) 2. Artificial intelligence (AI) is emerging with the potential to assist human decision-makers, particularly in high-pressure emergency scenarios. (17 papers) 3. Cybersecurity in a company's online services becomes a crucial focus. Safeguarding the companies entails ensuring the resilience of its online services and digital platforms against cyberattacks. (4 papers) 4. Digital leadership with a trust-based culture has solidified its position as a crucial aspect of organizational management. (8 papers)
Supply chain management aspect	1. The localization of suppliers and warehouses, along with centralized or decentralized manufacturing capacity, has emerged as a significant topic of discussion aimed at enhancing resilience during times of crisis. (11 papers) 2. Supply chain integration emerges as a solution to facilitate information sharing and enhance connectivity for effective disruption recovery. (13 papers) 3. Supply chain resilience was consolidated as a main strategy for companies when they were confronted with the possibility of supply chain disruptions affecting all facets of operations. (29 papers)
Business model aspect	1. Customer consumption patterns have changed since the pandemic: changes in demand for specific products and a customer preference for services with little physical and time-consuming intermediation. (17 papers) 2. Companies are establishing business-to-consumer (B2C) channels to connect directly with end-consumers. (14 papers) 3. Remote work was consolidated through the facilitation of digital transformation. (26 papers) 4. Despite the COVID-19 pandemic shed light on the discussion about the interface of servitization and resilience, the literature remains divided on whether servitization truly benefits resilience. (5 papers)
Innovation aspect	1. Agility has been vital for companies to adeptly address major societal challenges, including global health crises, by swiftly adapting their processes, business, and management practices. (16 papers) 2. The innovation process becomes strong with the companies' necessity to rethink how they could generate value from their current bundling of resources and what type of value they would like to create. (15 papers)

Aspects of OSCM transformations	Emerging topics in the literature of OSCM
Continuous improvement aspect	1. Lean manufacturing (LM) presents itself as an essential approach to improving a company's response in times of unprecedented crisis. (16 papers) 2. Just-in-time (JIT) system started to become criticized due to its lack of flexibility due to its focus on minimizing excess capacity and inventory, limiting agility. The literature raises uncertainty about the viability of JIT practices in a post-pandemic world. (16 papers)
Sustainability aspect	1. Corporate social responsibility (CSR) strategies have become imperative, prompting organizations to reassess their visions, missions, and objectives to align with the societal expectations of a post-pandemic era. (7 papers) 2. In the current business scenario, it is urgent the development of policies aligned with sustainability. In this scenario, the success of any company depends on the ability to impact the future of both humanity and the planet positively. (11 papers)

4.4.2 The legacy of covid 19 to OSCM and insight from industry practitioner

4.4.2.1 Technology aspects

The COVID-19 crisis has exposed vulnerabilities within supply chains, prompting companies to change from traditional models toward digital supply networks (DSNs). These DSNs prioritize seamless information flow, end-to-end visibility, collaboration, agility, and supply chain optimization (ZHU; CHOU; TSAI, 2020). Bianco et al. (2023b) developed a survey about the role of Industry 4.0 in developing resilience in manufacturing companies during crisis times. The authors show how leveraging Industry 4.0, encompassing smart manufacturing practices and capabilities, empowers manufacturers to improve their operations, swiftly address performance setbacks during global crises, and build resilience. Their findings underscore that Industry 4.0 adoption prepares companies with resilience by improving flexibility, reliability, robustness, and responsiveness. Complementing the literature one interviewee made the following statement regarding the application of technologies during the pandemic:

"In the aeronautical industry, I believe that technologies were particularly helpful during the pandemic by enabling connection and integration within the organization. The shift to a digital environment, supported by information technologies, facilitated remote work across various company sectors and efficient communication during the crisis. I observed that many of the technologies the company had been studying for several years were better applied during

the pandemic, such as those focused on the production environment and the use of virtual reality." (practitioner B)

DSNs leveraging cutting-edge technologies like IoT, AI, robotics, and 5G, are designed to anticipate and tackle forthcoming challenges. Adopting these innovations enables companies to proactively manage disruptions resembling those of COVID-19, effectively navigate market uncertainties, and proactively address future supply chain issues (ZHU; CHOU; TSAI, 2020). In parallel, information technology and digital solutions, including 5G, big data analytics, and cloud computing, empower firms to enhance visibility across multilayered processes, facilitating early disruption detection within intricate supply systems (XU et al., 2020). Moreover, factories reducing human involvement incorporate automated guided vehicles (AGVs), sensor networks, and remote operational mechanisms. These sensors continuously monitor on-site conditions, promptly signal significant events, and trigger alarms upon detecting abnormalities. Consequently, operators can remotely guide robots and swiftly address issues (SIRIWARDHANA et al., 2020).

The onset of the COVID-19 pandemic compelled an urgent shift towards digitalization of business operations and remote functionalities. What was once considered a 'nice-to-have' swiftly transformed into a critical necessity for survival within an increasingly uncertain business environment (AKPAN; SOOPRAMANIEN; KWAK, 2020). Smart applications offer a pivotal benefit in restructuring supply chains, particularly within agriculture, by ensuring the traceability of stages. This streamlined approach allows for the removal of intermediaries, effectively shortening the chain, and thereby enhancing both food safety and security (GURBUZ; OZKAN, 2020). According to Tripathi and Bagga (2020), in the healthcare sector, has grown the adoption of big data and predictive analytics. This adoption facilitates an enhanced understanding of drug discovery and innovations. Interactive analytics and business intelligence solutions' dashboards provide policymakers with nuanced insights, improving informed decision-making. One of the interviewees gives an interesting example of the application of additive manufacturing in the aeronautical sector:

"Additive manufacturing was crucial during the supply chain disruption as it allowed the company to produce and test some parts and components that were scarce in the market. With the supply chain breakdown, many suppliers struggled with product delivery due to compromised production capacity. Thus, additive manufacturing allowed for quick adaptations and testing." (practitioner B)

With the COVID-19 pandemic emerged the challenge of making timely, well-founded decisions across various sectors such as government, healthcare, public services, and commercial entities. Leaders at all decision-making levels, from strategic to operational, grapple with the urgency of effective decision-making. This crisis stands as the ultimate test for leadership and management who need to deal with unreliable information. Leaders face the daunting task of navigating critical decisions with limited or incomplete data due to the virus's unpredictable nature and rapid spread. The abundance of unreliable information and misinformation further complicates this challenge, necessitating filtering and sound judgment (DWIVEDI et al., 2020).

Addressing this challenge involves leveraging AI's capability to augment human decision-making. AI's rapid learning and ability to swiftly adjust decisions offer immense potential to expedite the decision-making process, particularly in emergency scenarios where human decision-makers operate under immense pressure (DWIVEDI et al., 2020). Intelligent manufacturing (IM) stands as a promising solution to enhance production efficiency amidst the demands posed by this ever-changing epidemic. IM operates by facilitating intricate, real-time decision-making within automated manufacturing assets, harnessing data sourced from networked machines and sensors (LI et al., 2020). One of the interviewees, in addition to being a practitioner of the aeronautical industry, completed a master's degree on the subject of AI applied to aviation and made the following considerations:

"In the aeronautical industry, the application of AI occurs, but with more caution. This is because there is significant concern for aircraft safety and information security. However, I believe AI is becoming increasingly useful. There are several initiatives for its application, generating data for decision-making. It's necessary to analyze data related to specific aircraft activities and general field data. Thus, efforts are being made to expand AI usage to assist in the collection and analysis of data for more precise and assertive decision-making. Nonetheless, I don't believe AI initiatives arose due to the pandemic; I think these initiatives were already in place before the pandemic. However, they certainly helped the industry navigate this crisis more resiliently." (practitioner E)

According to Dwivedi et al. (2020), cyber-attacks have increased amid the COVID-19 pandemic, once a concern primarily for tech-focused groups, these attacks now affect all types of organizations. Hackers are using different methods like ransomware and various other attacks to access valuable information. To protect against these threats, organizations need a twofold approach to be resilient against cyberattacks and protect organization's online services and digital platforms. The digital supply chain presents an opportunity to leverage technologies like radio frequency identification (RFID) and blockchain. These innovations can elevate information sharing and amplify visibility within the supply chain (CAI; LUO,2020). By integrating blockchain and AI, the organization could automate the supply chain and reduce human involvement. This automation ensures seamless operations during unexpected crises by establishing a reliable, secure system without constant human oversight. Blockchain implementation also sidesteps bottleneck processes that traditionally rely on human validation for transactions, benefiting organizational efficiency (DWIVEDI et al., 2020).

Overall, the aeronautical industry practitioners interviewed reported the sector's concern with information security, particularly in a pandemic scenario where various operations migrated online. One interviewee, an information technology manager, offered several important observations on this matter:

"Cyberattacks have significantly increased in recent years across the aeronautical industry. At the company where I work, we have greatly enhanced our layers of protection to ensure information security is preserved. We observed that many companies in the sector experienced data breaches during the pandemic. This prompted us to strengthen our data protection measures even further. We closely monitor each of our partners. Sometimes a partner is attacked, which leads us to adopt even stricter measures to protect against potential threats from partners. I would say that cybersecurity is an area in which the company has made substantial progress in recent years." (practitioner F)

Moreover, an interviewee from the Brazilian Air Force made the following comment regarding cyberattacks:

"Cyberattacks have always occurred within the Air Force. However, these attacks have become more frequent due to the Ukraine conflict; I do not believe they relate to the pandemic. Nevertheless, information security measures within the Air Force have been reinforced over the years. The pandemic has reinforced the need for information security. Improvements in information security aspects have enabled the Air Force to conduct video conferences for aircraft preparation for flights. Therefore, we hold encrypted meetings, eliminating the

necessity for in-person meetings involving many people. In the past, I often had to travel to Brasilia for meetings that I served merely as decorative items." (practitioner J)

The COVID-19 pandemic highlighted the vulnerability of the supply chain, necessitating companies to adapt to management approaches aligned with resilience and consolidate Industry 4.0 technologies. Nonetheless, this period with changes and challenges culminated in the establishment of a leadership model proficient not only in crisis management but also in fostering motivation and sustaining employee productivity within a remote work environment. This leadership model is commonly referred to in the literature as "digital leadership." Leadership models have evolved over time, in the same way that operations management and leadership also transform to sustain changes in the work environment. This transition, as discussed by Bass (1990), represents a shift from transactional leadership, which relies on a system of punishments and rewards, to transformational leadership, centered on charisma and motivation. Recent research on leadership has shown the need for leadership styles that foster trust and autonomy among employees (BIANCO et al., 2023a). These qualities are essential for the development of specific digital leadership competencies, including the preparation of people to interact with new technologies and aligning the organization's business model with the implementation of emerging Industry 4.0 technologies (BIANCO et al. 2021).

In a rapidly changing environment, like a pandemic, managers need to adapt their organizational structures, both internally and externally, while also safeguarding the organization's reputation and the interests of its stakeholders (YALLOP; ALIASGHAR, 2020). One significant change is the increased use of remote work, which some companies have continued to offer even after the pandemic. Traditional hierarchical leadership styles are ineffective in remote work settings, as the concept of command and control doesn't work well in a digital environment where physical distance reduces control (FENWICK et al., 2020). Recognizing this, forward-thinking organizations and leaders are embracing digital leadership. Establishing strong and effective leadership within a culture of trust is crucial to inspire people to work together creatively, even in remote working scenarios (ADŽIĆ; AL-MANSOUR, 2020; GURBUZ; OZKAN, 2020). Digital leaders recognize the importance of trusting their employees to responsibly exercise the new 'freedom' of remote work, and they also strive to be more accessible and approachable (FENWICK et al., 2020). Complementing the literature one interviewee who is a manager in the aeronautical industry made the following statement regarding leadership:

"With remote operations, it was indeed necessary to foster a culture of trust among employees. Leaders had to adapt to new ways of leading remote teams. Training was held to help people navigate this situation, as each individual reacts differently. Some feel more freedom working remotely, while others may experience increased pressure. Many employees faced challenges related to time management in this setting." (practitioner G)

Below is another interesting observation related to leadership during the pandemic:

"Before the pandemic, the manager used to sit at the back of the room, a position that allowed them to observe the work of all employees in real-time. With remote work, this was no longer possible, so leadership had to adapt to managing in a remote environment. Now, with employees working remotely, the leader can no longer see what employees are doing in real-time or observe their commitment to their work. The major shift was fostering trust in the workplace. Over time, it became clear that results remained satisfactory, as the emphasis shifted to the efficiency of delivering outcomes rather than simply appearing productive by staying focused at one's desk during the in-person workday. In this context, performance indicators gained greater importance." (practitioner E)

Leaders faced challenges when managing the COVID-19 crisis, particularly because of the context of high instability. A competent crisis leadership implemented an effective business continuity plan to optimize the company's overall crisis performance (TRIPATHI; BAGGA, 2020). To effectively deal with these turbulent times, they needed to adopt measures that aligned with resilience, digital transformation, and decision-making agility. Resilience became paramount as leaders had to ensure the organization's ability to absorb shocks and adapt rapidly to unforeseen circumstances. Digital transformation was not just an option but a necessity, as remote work and digital communication became indispensable tools for business continuity. Leaders had to swiftly embrace technology to maintain productivity and communication in the face of disruption (YALLOP; ALIASGHAR, 2020). Moreover, decision-making in an unstable environment requires a flexible and data-driven approach, with leaders relying on real-time information and scenario planning to make informed choices (DWIVEDI et al., 2020). Adapting to these measures, leaders were better equipped to guide their organizations through crises while promoting a culture of resilience, trust, and innovation.

Concerning the discussion about technological aspects transformations during the COVID-19 crisis, we develop the following proposition:

Proposition 1: The aeronautical sector, as a CAS, can adapt and coevolve in the face of a crisis by swiftly leveraging technology to support remote work, digital leadership, and enhanced cybersecurity.

4.4.2.2 Supply chain management aspects

Amid the unique challenges posed by the COVID-19 pandemic, the literature has discussed the critical aspects of centralization and decentralization in the context of supply chain management. As the global supply chain faced unprecedented disruptions, the examination of location-related strategies, such as centralization and decentralization, has emerged as a focal point for research and analysis. Decentralizing manufacturing capacity has the potential to alleviate the challenges encountered in the wake of the COVID-19 pandemic. Such a shift necessitates a departure from the prevailing centralized, large warehouse infrastructure, which prioritizes cost optimization, towards a more decentralized supply chain model characterized by numerous, smaller, regional warehouses strategically positioned in proximity to demand centers. This transformation demands a shift from strategies primarily centered on optimization to strategies that prioritize sustainability, agility, and resilience within the supply chain (DWIVEDI et al., 2020).

On the other hand, centralizing management within a single location has been a conventional approach. However, in the midst of the COVID-19 pandemic, an increasing number of companies are reevaluating their manufacturing strategies, considering the feasibility of bringing production in-house or closer to their home markets. This shift is driven by the desire to enhance resilience, with the underlying notion that in times of contingency, maintaining local suppliers at specific locations may prove more advantageous than relying on globally dispersed suppliers (ZHU et al., 2020; ISHIDA, 2020). Companies are actively realigning their supply chains by introducing additional local and nearshore suppliers and facilities, thus reducing their dependence on singular global sources. The insufficiency of production capacity in certain regions has highlighted the vulnerability of supply chains during times of crisis (REMKO, 2020; FREE; HECIMOVIC, 2021).

Overall, practitioners in the aeronautical industry reported a significant disruption in the supply chain, with various components for aircraft manufacturing being scarce in the market. They also noted that diversifying suppliers and decentralizing manufacturing in aviation is not simple, as suppliers must be certified by authorities. Consequently, there are limited suppliers available for critical components such as aircraft engines. Several interviewees made relevant comments on this topic, as can be seen below:

"The aeronautical industry's supply chain was significantly affected by COVID-19. For example, we needed an aircraft component from a supplier located in a region that was completely shut down and subject to embargos. Additionally, there were issues at ports and other logistical modes, which became disorganized and congested. As a result, aircraft manufacturing companies have suffered and continue to suffer significantly from the effects of this disruption in the supply chain. Adjustments are being made where possible, and companies are already looking to expand their supplier base. The pandemic highlighted this need. However, some challenges persist, especially when there is only one certified supplier for a specific product. There may be other suppliers for the same product, but only one is certified, limiting options. This situation required extensive management, stock information integration, and a closer relationship with suppliers." (practitioner F)

"Of course, the market is adjusting, but aviation already had a characteristic before the pandemic: dependence on a few suppliers. When an aircraft is certified with a specific engine supplier, you cannot simply switch to another supplier. You test the plane with that partner, obtaining certification with them. This is an example of several aircraft components, revealing a dependence on a single supplier. This has created additional challenges for aviation in the post-pandemic landscape. With the scarcity of raw materials to manufacture components or engines and the lack of skilled labor, especially among suppliers located in the United States and Europe, the pandemic has intensified this situation. As a result, we have faced many difficulties." (practitioner C)

“I see a market trend towards increasing the number of suppliers. However, I still believe that the model of having fewer suppliers and building solid partnerships ends up being a win-win situation that pays off. Maintaining a partnership with the supplier is much more valuable and ensures higher quality. We suffer less and achieve more. For me, quality is essential because the cost of repairing is much higher than the initial savings in buying the part.” (practitioner O)

"During the period of material shortages, we had to adapt and produce many things internally to meet our needs. Although we still face supply chain challenges, we have managed

to reassess our approach to determining whether it's better to buy or produce certain items ourselves. The supply chain was the most heavily impacted area, affecting our ability to manufacture and deliver products. This impact is still felt today, as some challenges have yet to be resolved, and this remains a global issue. In terms of which parts have been most difficult to obtain, our main challenges have been related to engines, which we do not manufacture in-house and must purchase externally. We also faced issues with smaller components, such as the aircraft's wiring systems, which we typically source externally but had to start producing ourselves. These material shortages led to extended production stoppages, affecting our ability to deliver products. As a result, we've had to engage in significant renegotiations with our clients." (practitioner A)

Overall, supply chain integration is essential for enhancing resilience and mitigating risks in the uncertain business environment. The synergy achieved by linking various supply chain components, including suppliers, manufacturers, and retailers, fosters the seamless exchange of real-time information and enhances coordination. This integration not only expedites responses to disruptions but also fosters a comprehensive comprehension of the supply chain. According to Paul and Chowdhury (2020b), It is necessary the information sharing and connectivity to facilitate disruption recovery. Moreover, the development of robust relationships with suppliers and the establishment of strategic partnerships, particularly across the sectors, emerge as vital strategies. Such collaboration enables companies to learn from different sectoral experiences and bolster their innovation capacity (GURBUZ; OZKAN, 2020). Enhance supply chain visibility, gain a comprehensive understanding of potential supply chain risks, establish safety stocks for critical items, strengthen operational resilience, and prioritize delivery reliability (FONSECA; AZEVEDO, 2020).

Amidst the COVID-19 outbreak, businesses are actively seeking to evolve their conventional supply chains into digital supply networks (DSNs). According to Zhu, Chou, and Tsai (2020), DSNs are characterized by the seamless exchange of information, end-to-end visibility, enhanced collaboration, flexibility, and optimization throughout the supply chain. An important aspect of this transformation is the digitization of buyer-supplier relationships, which not only strengthens supply chains but also identifies and engages new suppliers. To further fortify these supply chains, companies build transparency through analytics to identify weaknesses and do benchmarking. The integration of cutting-edge technologies such as the Internet of Things, artificial intelligence, big data, and related advancements is revolutionizing supply chain networks, rendering them into agile, intelligent workflows. This transformation not only enhances overall performance but also enables swift scenario planning and data-informed decision-making (FONSECA; AZEVEDO, 2020). Complementing the literature interviewees in the aeronautical industry made the following statement regarding supply chain integration:

"The supply chain in the aeronautical industry is highly complex and extensive, with multiple levels of suppliers. This has highlighted the need for more careful and comprehensive management. Companies have begun to manage not only their direct suppliers but also their suppliers' suppliers, and so on. This aspect of integration is important, involving processes such as site visits, risk management in the supply chain, and a closer approach. Companies have adopted market tools and systems to improve supply chain management, providing greater visibility. This not only benefits the company but also contributes to the overall maturity of the supply chain. Information flows more quickly and efficiently, facilitating management. Additionally, some technologies, such as inventory integration, have played a crucial role in this process." (practitioner F)

“There was a climate of intense dialogue and integration, particularly between suppliers and customers, as outlined in Porter's Five Forces model. Even passengers had to negotiate their airfare expectations, underscoring the impact of this challenging scenario. During the pandemic, aviation, especially passenger transport, was severely disrupted. The value of airplanes plummeted, and airlines that owned aircraft urgently sought any payments to avoid financial depletion. Negotiations were extensive, focusing on deadlines and deferred payments, with hopes that early signs of pandemic recovery would enable companies to resume operations and generate revenue to cover accrued monthly rents. These negotiations naturally involved decision-makers and suppliers, encompassing engines and other critical components. Between December 2019 and March 2020, the daily flights of a company that previously operated approximately 1000 flights per day plummeted dramatically to just 70. This resulted in the abrupt and substantial grounding of a significant portion of the airline's fleet. For example, a company with 150 airplanes had to ground at least 120 of them within a matter of months.” (practitioner K)

“During the pandemic, we observed a greater integration of the supply chain. We worked closely with our suppliers, implementing Kaizen initiatives collaboratively. We continued visiting some suppliers' plants, where we directly collaborated in production, providing

suggestions and enhancing communication. Many suppliers struggled to regain their previous pace, and to this day, some of us remain involved to assist in improvement efforts and communication, aiming to restore pre-pandemic volumes." (practitioner O)

Enhance resilience was consolidated as an important strategy for supply chain management. During the COVID-19 pandemic, successful companies recognize the need to develop robust mechanisms that ensure operational continuity and confer a competitive advantage. Such resilience within the supply chain is essential for companies to adapt, respond, and recover in the face of unprecedented challenges, enabling them to outpace their competitors and secure a stronger position in the market. Supply Chain Risk Management (SCRM) has been cited as a solution to improve resilience. It involves the establishment of policies and decision-support mechanisms aimed at addressing potential supply chain pandemic outbreaks. To achieve better outcomes for SCRM, a key element is the establishment of relational governance with supply chain members, including suppliers, customers, and other stakeholders (BAZ and RUE, 2020).

According to Fonseca and Azevedo (2020), supply chain executives strategically boost supply chains for resilience by building in redundancy across suppliers, increasing the inventory of critical products, nearshoring and expanding the supplier base, reducing the number of unique parts, and regionalizing their supply chains. Besides the authors pointed out that in response to evolving challenges, two critical new Key Performance Indicators (KPIs) have emerged: Time to Recovery, representing the duration for a node's full functionality restoration after a disruption, and Time to Survive, denoting the maximum duration for the supply chain to align supply with demand post-supplier or node disruption. This points toward an unlikely return to the "old normal, it is likely that successful companies will focus on creating a new kind of operational performance that emphasizes risk mitigation in supply chain management.

Several aeronautical industry practitioners reported that it was necessary to develop specific mechanisms and strategies to remain resilient during the pandemic. The following are some examples provided by the interviewees:

"To remain resilient in the face of the crisis, we had to adapt our production process. For example, we encountered supply issues with the aircraft engine, which is a very heavy part of the plane. There is a specific point in the production line when the engine must be installed. Even during aircraft assembly, care must be taken not to unbalance the aircraft's center of gravity or stress the landing gear. Therefore, we had to develop a temporary ballast to

substitute for the engine so we could continue assembling the aircraft. This prevented the entire production line from being delayed due to the absence of the engine. As a result, we made changes to production sequences and developed tools and equipment that compensated for missing parts, allowing the assembly line to continue running. This was a significant impact and learning experience during the pandemic. Contracts for engine supply are meticulously prepared to avoid delays, but the pandemic introduced unforeseen challenges." (practitioner E)

"At our company, we developed a post-COVID-19 recovery plan that brought in-house many activities previously outsourced. For example, we are considering developing our specific components as alternatives to external suppliers. This approach was prompted by the challenges faced during the pandemic when we identified opportunities to leverage our internal expertise and produce certain items ourselves to be more resilient." (practitioner N)

"I am sure that we developed mechanisms to remain resilient during the crisis, particularly concerning the shortage of parts. Delays in part deliveries began to occur, but we managed to maintain production. For instance, when a part was missing at a specific stage of assembly, we looked for ways to avoid halting production, such as installing that part at later stages. Of course, we faced sequencing constraints; we could not install one part if another part it depended on was not yet available. However, our resilience manifested in seeking internal alternatives to address the lack of parts without waiting for the supply chain to return to normal." (practitioner B)

"To ensure that you are better prepared when a crisis emerges, this is a question that has been debated for decades across various spheres of life. It involves both immediate and long-term concerns, along with power dynamics and corporate vanities. This is something that will continue to be debated for a long time, but it offers a universal lesson not only for aviation but for all organizations. Preparing for crises does not merely entail predicting the crisis. In aviation, for example, discussing safety is not about predicting an imminent disaster. It requires balancing the approach with the same ease that companies discuss safety, possibly applying this approach to crisis management as well. Preparing for a smooth landing does not necessarily mean predicting where turbulence will occur, but rather being capable of managing the necessary processes. This principle also applies to supply chain management. During a crisis, you need to be ready, having already secured agreements with suppliers and established

contracts. This may involve strategies such as negotiating fuel procurement contracts in advance, a significant part of airlines' operational costs, comprising about 35% to 40%. This is crucial because the price of oil, sourced from geopolitically unstable regions like the Middle East, is always subject to fluctuations, as are exchange rates. For instance, some companies employ strategies of early purchasing to stabilize payments and avoid surprises from unexpected price hikes. This approach can be applied to other operational areas as a sign of business maturity." (practitioner K)

Concerning the discussion about supply chain management aspects transformations during the COVID-19 crisis, we develop the following proposition:

Proposition 2: The aeronautical sector, as a CAS, self-organizes to emerge an integrated supply chain, enhancing resilience and developing mechanisms to overcome crises.

4.4.2.3 Business model aspects

COVID-19 has enabled a change in consumer behavior, with a growing comfort among individuals in using digital platforms and engaging in digital commerce. Companies must invest in advanced data analytics technologies, allowing them to gain deeper insights into changing consumer sentiment and offer a diverse range of service channels that align with consumers' expectations (DWIVEDI et al., 2020). According to Almeida et al. (2020), even though there are different business models, a prevailing expectation is that consumers will increasingly favor models granting them autonomy in selecting and contracting services or products, eliminating the need for physical and time-consuming intermediation. Simplification and integration enhance the customer experience, both serve to streamline interactions with customers and harness data intelligently. The COVID-19 pandemic will lead to a surge in consumer inquiries concerning the data stored about them and their utilization. Organizations must formulate data strategies that empower customers to control their shared information, showcasing the potential benefits of data usage for the greater good. They should transparently illustrate the specific advantages consumers can gain from their data disclosures (YALLOP; ALIASGHAR, 2020).

We can expect a change in consumer behavior because of disruptive technology. Besides, consumers may discover new talents as they spend less time on the road and more at home. As they experiment with cooking and acquire new skills, some may even explore commercial opportunities. Although most habits are expected to revert to normal, some may fade due to adaptation to the new norm. This desire for in-home activities has notably affected impulse buying, leading to increased demand for takeout, snacks, alcohol, and cleaning products (DONTHU; GUSTAFSSON, 2020). Consumers in many countries initially exhibited alarmist behavior, leading to panic buying of food and sanitary products. At the private level, consumer sentiment is evolving, as limited access to goods and services prompts citizens to reassess their purchasing patterns and prioritize essential items. Moreover, the COVID-19 pandemic has heightened awareness of the social consequences of individual lifestyles (IBN-MOHAMMED et al., 2020). The COVID-19 pandemic has implications for consumer ethical decision-making during and potentially after the pandemic. The pandemic taught consumers a lesson when promoting the reflection on the broader impact of their consumption choices, emphasizing the interconnectedness of these choices with society and the environment. The disruption of global supply chains encourages local purchasing, and there is an increased focus on health and wellness products, particularly those related to addressing the pandemic, such as vitamins and medical supplies (HE; HARRIS, 2020).

In the aeronautical industry, interviews revealed that the pandemic changed consumption patterns. Several interviewees reported that due to the social isolation restrictions imposed by some countries, demand for commercial flights dropped drastically. Consequently, demand for manufacturing commercial aircraft that carry a large number of passengers decreased during the pandemic. However, there was an increase in demand for the manufacturing of aircraft for executive flights and cargo transport.

Despite these changes, interaction with the end customer remained unchanged, with the process continuing to take place in person. Below are some comments from the interviewees on this topic:

“For the aeronautical industry, online sales are uncommon. It's a very different model when compared to other sectors such as retail. The dynamics are very specific. It's unlikely that the aeronautical industry will ever have a sales process similar to retail, as purchasing an aircraft worth millions of dollars is not the same as buying a pair of shoes. The sales process is highly technical, and in this regard, there have been no significant changes.” (practitioner F)

Before the pandemic, there was high demand for commercial flights with a large number of passengers, more than 200 people on a single plane. With pandemic restrictions and concerns about flying with others, demand for executive and private flights increased *significantly. This had a considerable impact on our company, as we manufacture both types of aircraft. Many clients who began using executive aviation during the pandemic out of necessity continued in this category after the pandemic. This change in consumption patterns has persisted in the post-COVID-19 world. (practitioner B)*

"With the exponential growth of online sales, demand for air cargo transportation increased significantly. Airlines seized this opportunity by converting passenger planes into cargo planes to support e-commerce companies. The pandemic led the aviation industry to adapt and focus on cargo planes. My company launched a new product to fill a gap in the market. During the pandemic, airlines converted passenger planes for cargo transport by removing seats to create space for goods. In this way, the industry generated revenue and offset the decline in passenger traffic caused by the closure of airports for nearly two years. The adaptation to serve the e-commerce sector was an important change observed during this period." (practitioner C)

The COVID-19 pandemic challenged companies to embrace new internal operational methods and companies have faced substantial pressure to expand their product offerings through digital channels. Notably, the pandemic exerted a substantial influence on the surge in online commerce growth, primarily attributed to trade closures and mobility restrictions (ALMEIDA; SANTOS; MONTEIRO, 2020). Became imperative for companies to enhance their agility, boost productivity, and establish direct connections with end-consumers while safeguarding their financial stability. These changes prove the adaptations of business models and the transition from Business to Business (B2B) to Business to Consumer (B2C) operations and embracing e-commerce. An example of this is leading retailers with physical stores that closed during the pandemic. Companies needed to effectively tap into online and direct-to-customer sales channels, even delivering essential goods to customers confined to their homes (FONSECA; AZEVEDO, 2020).

New business models that emerged during the pandemic have been consolidating with digital transformation, which was accelerated for companies not to be as vulnerable to the next crisis. This transformation would enable companies with the ability to effectively respond to internal and external environmental changes while still creating value, which requires the company's analytics capabilities (DWIVEDI et al., 2020). A business model with digital technologies as a reference point should encompass, the potential for remote work, flexible scheduling arrangements, the automation of the supply chain, and direct connection with end-consumers. Therefore, the B2C business model seems to be the trend for strengthening organizations in the post-COVID-19 world (NIEWIADOMSKI, 2020).

In the aeronautical industry, the B2C model already existed before the pandemic, as aircraft manufacturers also attend to the demand for executive aviation. This business model intensified during the pandemic due to the increased demand for aircraft for executive and private flights. While technology enabled communication with the end customer without physical contact in some instances, most of the time this process remained in-person, as reported by the interviewees:

"The connection with the end customer has strengthened significantly in aviation. Being close to the customer is an advantage; the closer the relationship, the better the outcome. It is essential to be available when needed, as any operational interruption can cause losses for both aircraft owners and maintenance companies. It is important to understand the customer's needs and strive to meet them in the best possible way for both parties. Although this relationship has intensified, online sales in aviation remain limited. People want to know, understand, and experience the aircraft before making a decision." (practitioner B)

Remote working has become an option for millions of workers, but a cultural shift is necessary to improve result orientation and entrepreneurship in all employees (RAPACCINI et al., 2020). From the COVID-19 experience, with prolonged periods of lockdown, remote work was consolidated in a lot of companies (DWIVEDI et al., 2020). Transitioning from face-to-face work to remote work should be accompanied by concurrent efforts to reshape organizational culture and undergo digital transformation. A culture that supports remote work recognizes that success is measured by outcomes rather than the hours spent at a desk. It is necessary to promote trust, autonomy, flexibility, and empower employees to manage their work effectively from anywhere. Embracing this change is essential for attracting top talents and for staying competitive in a post-COVID-19 world when remote work is increasingly the norm.

Remote work has become a reality, so the employees commenced it to the extent feasible. In instances where remote work was not a viable alternative, organizations undertook the reconfiguration of work shifts and the restructuring of workstations. It has become necessary to redesign management and collaboration models to ensure that nobody within organizations is left behind and feels excluded from this digitization process (ALMEIDA et al., 2020). This practice has now gained widespread acceptance among the majority of companies. In the post-

COVID-19 world, companies will need to strategize on the continued facilitation of remote work for a significant portion of their employees, as it reduces the need for office space and related costs (DWIVEDI et al., 2020).

In the aeronautical industry, there was a paradigm shift regarding remote work. The interviewees reported that before the pandemic, even though there had been discussions about remote work, the possibility was far from becoming a reality. There were various concerns about ensuring the quality of operations and aircraft production, as well as worries about information security and data sharing in a remote work environment. These considerations are evident in the following comments from the practitioners:

"In the information technology aspect, a notable achievement was the rapid transition to remote work, with a large number of people working from home overnight. This required changes in tools and connectivity, but the company was prepared and managed to maintain productivity. The future of aviation will need to address issues related to preserving an aeronautical culture with employees accustomed to remote work. The company I work for, for example, has increased in-person work in some areas to maintain the company's culture. Some companies are returning to partial or full in-person work to preserve their corporate culture." (practitioner F)

"Remote work became established for many businesses post-pandemic, and the same occurred in the aviation industry. Before the pandemic, operations were entirely in-person, with no clear plan for transitioning to online work. However, during the pandemic, several administrative activities, such as those related to office work, proved feasible to carry out remotely, and this practice continues today. For example, areas like supply chain and administration can operate 100% remotely, while engineering may adopt a hybrid model with some days in the factory and others at home. Each department has the autonomy to define its work policy. Overall, remote work has been successful, with productivity and efficiency improving as employees work from home." (practitioner A)

"I never imagined working from home. I always thought it wouldn't be possible for my type of work. However, the pandemic showed me it's feasible, and some activities remain in the digital environment to this day. For instance, during the pandemic, we learned to conduct Kaizen online. Beforehand, we used to stick papers on the wall with post-its to map processes and identify issues. It took a lot of effort to map, gather evidence, and record everything while everyone was in the room. During the pandemic, we started using online tools for Kaizens. So

now, in the post-pandemic world, when we plan a Kaizen, we gather everyone in the room, each with their computer, to do it electronically. Everyone posts their ideas, and all contribute." (practitioner O)

"I believe the main legacy of COVID-19 for the aeronautics industry was remote work. For aeronautics, remote work emerged as a possibility during the pandemic and has remained, even if not in a fully integrated manner. Virtually all areas of the company, including those where in-person work is somewhat essential, developed the flexibility to operate remotely, even sporadically, during the pandemic. In the manufacturing sector, before the pandemic, employees needed to be physically present at the factory almost every day. Nowadays, even manufacturing employees can plan to work remotely. This was something nearly unthinkable in the past. Therefore, this was a significant legacy of COVID-19 that is here to stay." (practitioner P)

Servitization, the transition from a product-centric to a service-centric business model and mindset (KOWALKOWSKI et al., 2017), offers a means for manufacturing firms to bolster their business resilience during periods of crisis. Even when clients face constraints on purchasing new products due to financial constraints and supply chain disruptions, existing products still demand routine maintenance and service. Consequently, manufacturers can continue to offer spare parts and deliver high-margin field services, including maintenance, repair, and overhaul, ensuring ongoing revenue streams (RAPACCINI et al., 2020; OKORIE, et al., 2020). Rapaccini et al. (2020) conducted an extensive survey and interviews during the COVID-19 pandemic, emphasizing the significance of servitization business models and the rapid advancement of digital transformation and advanced services. The authors highlighted the importance for industrial firms to strategically evolve towards service-oriented approaches, crafting digital product-service offerings while preserving their substantial industrial expertise accumulated over decades of competition in the engineering sector. Consequently, digital servitization emerges as a strategy to explore how radical changes and additional digital resources, which may be less susceptible to certain crises, should be both developed and leveraged.

On the other hand, the survey developed by Li et al. (2022) shed some light on the "dark side" of servitization. The research findings showed that manufacturing companies with high levels of servitization struggled more during the COVID-19 pandemic. This suggests that adopting servitization requires firms to make significant adjustments in their resources, organizational structure, culture, and buyer-supplier relationships to address the difficulties related to providing services. The pandemic exacerbated these challenges by disrupting transportation, limiting human interactions due to social distancing, and imposing lockdowns at local and global levels. The pandemic underscored ongoing discussions about the merits and drawbacks of servitization while also paving the way for research at the intersection of servitization and resilience.

The interviews conducted in our research show that servitization is not a common practice in the aeronautical industry. However, some projects in parts of the production line evaluate the benefits of renting a robot to perform certain functions instead of purchasing the robot. Below is a comment from one of the interviewees regarding this business model:

"Especially in the area of automation, we are considering different business models, such as acquiring services instead of purchasing equipment. For example, instead of acquiring a robot for the factory, we are evaluating the possibility of renting the services of an integrator for a specific period. This involves purchasing the service of a robot, which is similar to leasing. This approach is being analyzed to understand whether it is more advantageous to buy the resource or contract the service of an integrator. During the pandemic, we found that this type of contract can offer benefits; however, the evolution of this business model is not necessarily related to the pandemic. Rather, it is an emerging trend that allows flexibility in operations. In our experience, we did not face significant issues with service provision during the pandemic. Social distancing did not impact the maintenance of services." (practitioner D)

Concerning the discussion about business model aspects transformations during the COVID-19 crisis, we develop the following proposition:

Proposition 3: The aeronautical sector, as a CAS, coevolves in the face of a crisis by adapting its business model to migrate to remote work, identifying changes in consumption patterns, and connecting with end consumers.

4.4.2.4 Innovation aspects

Agile companies operate as learning organizations, focusing on enhancing their analytical capabilities (GURBUZ; OZKAN, 2020). The necessity for entrepreneurial agility became apparent with the rapid spread of COVID-19, demanding organizations to adapt swiftly amid hypermobility (HE; HARRIS, 2020). Agile approaches promote flexibility, providing a project's scope that can intermittently evolve alongside the necessary supportive resources. These techniques are notably preferred in scenarios that demand heightened stakeholder involvement and shorter turnaround times for delivering outcomes, like the pandemic environment (KUDYBA, 2020).

According to Rapaccini et al (2020), agility could be a defining element of resilience once it represents a company's capacity to swiftly adapt to dynamic changes, encompassing shifts in both volume and diversity. In effectively addressing societal challenges, strategic agility becomes pivotal for companies. It demands the development of capabilities to swiftly reconfigure business and managerial approaches amidst a global health crisis. Companies could harness their inherent flexibility and agility in responding to market and societal needs, exemplified by their rapid adaptation in producing personal protective equipment by quickly reconfiguring their production setups (LIU, M. LEE, C. LEE, 2020).

The interviews conducted in our research indicate that the aeronautical industry employs strategies aligned with agile methodologies, which enabled changes in production processes to meet unexpected demands during the pandemic, such as the increase in demand for executive aircraft and cargo transport. The following comments exemplify this aspect:

"I am confident that the aeronautical industry employs agile strategies to align production with new market demands. In aviation, it is very evident that the various players are actively pursuing innovation." (practitioner I)

"In the general aviation industry, innovation is more closely related to technology. The company I work for, for instance, is frequently recognized for its innovation in Brazil, both in products and processes. Additionally, many companies are exploring new markets, such as electric aircraft, and investing in research on renewable fuels to position themselves in the market and meet international regulations. There are also innovations in Electric Vertical Take-Off and Landing (eVTOL) vehicles (flying cars), a completely new product with an uncertain market, but already in the testing phase. The pandemic did not halt these innovation processes, which continue to progress, including internal innovations such as the adoption of Industry 4.0 and artificial intelligence. This helps companies become more competitive and explore new markets. However, budget constraints caused by the pandemic led to the postponement of some projects, with companies prioritizing the maintenance of cash flow." (practitioner F)

The COVID-19 pandemic has opened opportunities for companies to foster innovation by reimagining their existing products (SEETHARAMAN, 2020) and identifying ways to create value by addressing the challenges posed by the crisis, such as developing solutions for hygiene or digital work (KUCKERTZ et al., 2020). During a pandemic, companies must reconsider how they utilize their resources to create value. For instance, Louis Vuitton repurposed its fashion and cosmetics facilities to produce essential items like masks and hand sanitizer, benefiting society even if it doesn't provide a lasting competitive edge. After a pandemic, firms may return to some previous resource allocations while permanently changing others. As seen with Louis Vuitton, coordinating resource structure, bundling, and utilization will be essential for preparing for future pandemics (CRAIGHEAD et al., 2020).

Gorzelany-Dziadkowiec (2021) developed a survey and de findings suggest that companies capable of innovation would have better ways of handling uncertainty during the COVID-19 pandemic, so it is imperative for businesses to enhance their innovation capabilities. A culture of innovation encourages employees to contribute ideas, thoughts, and suggestions for improvement within the organization. This "idea box" approach can be implemented even before a formal return to the workplace, by encouraging employees to contemplate what information or process changes might enhance their job's efficiency and ease. Utilize this period of isolation to collaborate with employees and across departments to explore positive transformations (TRYBULA; NEWBERRY, 2020). In a post-COVID-19 world is important to think about how we can leverage and transform the challenges into new opportunities, both in business and internal organizations (ALMEIDA; SANTOS; MONTEIRO, 2020).

The aeronautical industry can contribute during the pandemic by creating value for society by adapting its production to assist in the manufacturing of valves for respirators, as reported by some interviewees. The following statement from one of the interviewees was noteworthy in this regard:

"Several companies with production facilities contributed in some way during the pandemic, including the company I work for, which adapted its production process to supply parts to companies manufacturing respirators. Our plant, which specializes in landing gear and fluid control valves, participated in this effort. At the time, we received a project due to the increased demand for valves for respirators and were able to expand our capacity to meet the demand. This was an important contribution during the pandemic. Although it was a temporary initiative, it was very gratifying to help in this way." (practitioner E)

“The company I work for established a study group during the pandemic to develop the technology currently used in aircraft for air conditioning system air filtration, one of the best available air disinfection technologies. This is because the air inside the aircraft is recirculated, and external air cannot simply be brought in. Therefore, there is a comprehensive disinfection system to prevent the spread of diseases. The company also collaborated with hospitals to implement this technology within their facilities. What became very clear to me is the sector's ability to contribute to other important aspects and businesses for society.” (practitioner Q)

Furthermore, it was the Brazilian Air Force that transported equipment and patients, thereby contributing to caregiving during times of crisis, as evidenced in the following report:

“In the Air Force, it was necessary to develop protocols swiftly, demanding our readiness. One of our functions is aeromedical evacuation. However, we had never before encountered such a level of risk. Throughout the COVID-19 pandemic, the Air Force handled all processes of transporting equipment and patients between Brazilian states. Crew members had to take appropriate precautions. This adaptation was necessary to continue operations and facilitate these transports. The Air Force demonstrated remarkable agility in this regard. Due to this work, I had a squadron colleague who passed away from COVID-19, and even conducting rescues was challenging. Therefore, swift adaptation was crucial to meet the population's needs.” (practitioner J)

Finally, one of the interviewees reported that some marketing strategies were also developed to create value for customer:

Some companies sought to use preventive measures during the pandemic as a competitive advantage, including regular disinfection with 70% alcohol during overnight stays of airplanes and the adoption of ultraviolet light devices for internal aircraft disinfection. Additionally, they distinguished themselves by the airplanes' ability to effectively filter the air, promoting these practices as part of air travel safety. Companies also enforced the mandatory use of masks by employees, employing marketing strategies to convey a welcoming and secure demeanor to passengers, even with their faces partially covered. (practitioner K)

Concerning the discussion about innovation aspects transformations during the COVID-19 crisis, we develop the following proposition:

Proposition 4: The aeronautical sector, as a CAS with a nonlinearity feature, where small events can cause significant effects, emphasizes agile approaches to overcome crises and innovate to create value for society.

4.4.2.5 Continuous improvement aspects

As an approach based on operational excellence, LM played an important role in improving companies' responsiveness during COVID-19 and has contributed to facing challenges in the post-COVID-19 world. Bianco et al. (2023c) showed that LM's excellence is not lost during crisis times, lean companies have a culture of problem-solving and innovation that helps companies during crises. Certain academic articles about Lean environments may convey the erroneous impression that LM is about inventory reduction (e.g. FREE; HECIMOVIC, 2021; NANDI et al., 2020; XU et al., 2020; IKRAM et al., 2020) and suggest that embracing this approach could place companies at a disadvantage, particularly during periods of crisis. The adoption of lean practices and continuous improvement led the company to a problem-solving and customer-oriented culture. Paradoxically, the considerable degree of process standardization inherent in a lean implementation favors a company's flexibility, aligning with unexpected process redesign, as imposed by the pandemic (TORTORELLA et al., 2020).

Remko (2020) highlighted how Nike was an example amid the pandemic, leveraging the crisis to consistently change its product lines and mix. This strategic approach empowered Nike to rapidly adapt its production capacity in response to unexpected demand fluctuation, thereby enhancing the overall flexibility of its supply chain. While industry insiders confirm a degree of increased investment in inventory, agility is not about inventory cost, nor does a commitment to lean principles mean reducing inventories to reach cost reduction. Inventory reduction is a result of operational excellence reached with a lean philosophy. The term "leagility" emerged in the literature in order to utilize the benefits of agile and lean strategies and overcome weak points. While the lean strategy is very important for waste elimination the agile strategy is developed to take care of the speed and flexibility of the supply chain (RASHAD; NEDELKO,2020).

Besides the operational advantages of Lean companies, during the pandemic, employees who were adapted to this philosophy maintained productivity in the home office environment. According to Tortorella et al. (2020) companies that have been implementing lean more extensively, could also extend advantages from this philosophy in the context of remote work during the pandemic. Effective lean implementation can engender not only transformations in the practices and methodologies employed within the company but also instill novel work habits that significantly influence individual behaviors. The employees replicate their work habits and behaviors in their home office environment, which would lead to similar benefits as the ones observed within the company.

There are challenges in a post-COVID-19 world, such as adapting to health and safety measures (MOLLENKOPF et al., 2020), developing policies aligned with sustainability (FERRANNINI et al., 2021), adopting technologies, and digital transformation (FREE; HECIMOVIC, 2021; REMKO, 2020). Lean played an important role during the pandemic, but Lean has also helped companies overcome the challenges of the post-COVID-19 world. The empirical research carried out by Bianco et al. (2023c) showed that Lean companies have an open culture for change and innovation that allows the development of efforts to transform Lean companies into companies aligned with the future of operations management and adapted to the trends of the post-COVID-19 world.

The interviews conducted in our research corroborated the information gathered in the SLR. The aeronautical industry exhibits a high level of maturity in Lean Manufacturing, and there was consensus among the interviewees that Lean helped organizations remain resilient throughout the pandemic, as reflected in the following comments:

“Lean organizations were undoubtedly more resilient than others during the pandemic. The company I work for, which manufactures airplanes, has a high maturity in Lean philosophy, and this certainly helped during the pandemic. Regarding suppliers, those with greater Lean maturity responded more quickly to the crisis. Here, we frequently use Kaizen. So, I believe we are always prepared to change because we are in constant evolution, seeking continuous improvement. This greatly assists us in times of crisis, where we already know how to act in the face of constraints. People are more prepared for changes, I would say that this is the major differentiator of Lean organizations.” (practitioner O)

"In my opinion, the pandemic did not strengthen the Lean culture within the company because it was already very strong. However, it prompted the company to reflect more on Kaizen and improvements to adapt to the new reality. The quick, unplanned transition to the digital environment led to processes needing to be redefined and information becoming misaligned. Consequently, the company utilized continuous improvement tools to structure more robust processes, adapt to this new scenario, and navigate the supply chain disruption

more resiliently. Therefore, it is not a matter of an absent culture, but rather a greater emphasis on projects to handle abrupt changes." (practitioner C)

"The company I work for applied Lean to overcome challenges during the pandemic. Today, our management is strongly oriented toward Lean, integrating it into the company's culture. We frequently discuss processes and engage in Kaizen. Recently, we have conducted benchmarks with Toyota to understand how they build their indicators and manage certain processes, aiming to bring these practices to the aeronautical sector. This has been a highly enriching experience. I cannot pinpoint a single area where Lean has helped us, as it was already deeply ingrained in the company's culture, making its effectiveness second nature to us." (practitioner F)

The operations management literature raises uncertainty about the survival of the JIT system in a post-COVID-19 world. Free and Hecimovic (2021) developed a case study approach, reviewing the automotive manufacturing sector in Australia. The authors pointed out that for decades, low-cost supply and minimal inventory have been a focus of supply chain management. Nevertheless, in the scenario of a global disruption, like the COVID-19 pandemic, these management features have revealed vulnerability in supply chains. The implementation of just-in-time manufacturing has significantly reduced inventory levels. However, this has revealed supply chain shocks and shortages, thereby diminishing supply chain resilience.

Zhu et al. (2020) assign to JIT the medical supply chain's vulnerability. The authors discuss that the adoption of the JIT philosophy, which prioritizes efficient, timely deliveries left the medical supply chain susceptible to unforeseen disruptions. The rapid spread of the pandemic led to a surge in demand for medical equipment, surpassing available supplies. The advancement of global supply chains focused on reducing costs through efficient inventory management like the JIT system, has historically led to significant savings and profitability. However, the COVID-19 pandemic has exposed a downside to this approach, as it left many supply chains overly tight and fragile, lacking backup supplies during crises.

Fonseca and Azevedo (2020) point out that for better performance in times of crisis, companies must migrate from the JIT system to the “just-in-case” system. In the "just-in-case" system, companies maintain sufficient inventory levels to mitigate supply and demand uncertainties while emphasizing a balance between efficiency, flexibility, resilience, and reliability across the entire supply chain. Companies prioritize operational continuity over eliminating all inefficiencies and waste throughout the supply chain. However, adopting a "just-in-case" system is necessary to maintain extra inventory to handle potential delivery delays, which results in added costs and contradicts the JIT methodology. In a "just in case" system companies create contingency plans, accept potential increases in procurement costs and delivery times, favoring reliable over inexpensive suppliers, and place a strong emphasis on enhancing visibility, supply chain processes, and technology throughout the supply chain (FONSECA; AZEVEDO, 2020).

Although JIT has been criticized in the literature during the pandemic, this concept has been important for the aeronautical industry. According to the interviewees, low inventory levels may have negatively affected the supply chain to some extent during the pandemic; however, the interviewees believe that increasing inventory levels is not feasible for aviation.

Therefore, it is believed that the JIT concept will remain strong in aviation in a post-COVID-19 world, as reflected in the following comments:

"I understand the concern about low inventory levels and potential supply chain disruptions, but I believe that the JIT culture will persist post-pandemic. The post-pandemic scenario may adjust with new suppliers and supply chains. Technological advancements, such as new, faster transportation methods and greater access to information, allow for better inventory level definition. Artificial intelligence and agile communication with suppliers and customers also contribute to improvements in inventory management. However, this improved communication and integration among the elements of the supply chain will enable JIT to continue in the future, reducing uncertainty regarding the supply of items." (practitioner C)

"JIT is very important in aviation. I believe that initiatives to reduce inventory are ongoing in the company. Even though we experienced a shortage of some components, such as engines, I don't believe that holding larger stocks of this item will be the solution. In fact, it is unfeasible due to the cost. However, the JIT concept may have hindered operations due to the specific context of the pandemic." (practitioner E)

Concerning the discussion about continuous improvement aspects transformations during the COVID-19 crisis, we develop the following proposition:

Proposition 5: The aeronautical sector, as a CAS, with dynamic learning features, remains aligned with continuous improvement and a lean culture to build resilience in the face of crises.

4.4.2.6 Sustainability aspects

The COVID-19 pandemic has underscored that both individuals and companies thrive through mutual support and collaboration. Recent years have witnessed an evolution in the business approach, with an increasing emphasis on collective effort involving all parties as partners rather than isolated stakeholders. This shift indicates the emergence of a new business model that prioritizes social responsibility (AL-MANSOUR; AL-AJMI, 2020). Organizations will need to re-evaluate their visions, missions, and objectives to account for changes to their customers and competitors, amongst other shifts (DONTHU; GUSTAFSSON, 2020). The pandemic's impact has been far-reaching, disrupting supply chains, overwhelming hospitals with countless patients, and forcing the closure of schools. This crisis has underscored the pressing need to address the social aspects while emphasizing the necessity to enhance productivity, fortifying resilience in the face of COVID-19 (KHURANA et al., 2021). Therefore, the COVID-19 pandemic has emphasized the company’s role in supporting communities and addressing societal needs during times of crisis.

According to He and Harris (2020), there is an optimistic outlook that the crisis will accelerate the long-term evolution of corporate social responsibility post-pandemic. As companies increasingly recognize the critical link between sustained success and achieving a balance between profitability and harmonious stakeholder relations, the focus shifts towards not whether to invest in corporate social responsibility, but how to invest in it. The central question for future research is about strategically investing in corporate social responsibility to harmonize social, environmental, and economic goals for mutual benefit and interdependence. The prevailing societal guiding principle that prioritized efficiency and economic gain over safety, may potentially change in the world post-COVID-19 pandemic (DONTHU; GUSTAFSSON, 2020).

In the aeronautical industry, according to interviews conducted in our research, the policies of organizations are aligned with social responsibility, and during the pandemic, the care for people became evident, as seen in the following comment:

“In my opinion, companies have started focusing more on social responsibility, both within and outside the organization. There have been significant changes, especially regarding care for people. This included incentives for vaccination and the adoption of remote work. For instance, the occupational safety team, which used to focus solely on the internal environment, began to consider the well-being of employees at home. Measures were taken to ensure that

employees had an appropriate work environment at home, such as ergonomic chairs and desks. This required the company to extend its responsibilities beyond its premises to reach employees' homes." (practitioner A)

"In 2021, the company I work for established a sustainability goals plan. Some of these goals are related to maintaining the highest standards of corporate governance and safety. Other goals are aimed at combating climate change, focusing on reducing emissions in both the company's operations and products. Additionally, diversity goals were set, focusing on gender inclusion, persons with disabilities, and other diverse groups within the company. These goals aim to ensure significant representation within the company." (practitioner Q)

The COVID-19 outbreak, while temporarily reducing pollution and allowing nature to reclaim, presents a potential hope for sustainability. However, this positive environmental impact might be short-lived unless society learns from the lockdown and implements long-term pollution reduction measures. Organizations are actively boosting sustainability by integrating it into strategic decisions, employing green chemistry, and embracing eco-friendly practices (BARREIRO-GEN, LOZANO, ZAFAR, 2020). Furthermore, in today's economic scenario, the success of any company should be based, not only on profitability but also on its commitment to shaping the planet's future (KHURANA et al., 2021).

An economic restructuring is going to happen in a post-COVID-19 world. This unique situation offers an opportunity to change product systems onto a more sustainable path. Addressing this scenario necessitates designing and implementing new protocols for handling materials and products in the supply chains, alongside the integration of resilient mechanisms within these supply networks (VARBANOV, JIA, LIM, 2021). Nandi et al. (2020) outlined several strategies for sustainable supply chains in a post-COVID-19 era. These strategies encompass the utilization of products, components, materials, and resources across supply chains, coupled with efforts to shorten, narrow, or close resource loops for optimal material recovery. Enhancing product designs and supply chains to curtail waste and pollution, encouraging prolonged product use, and facilitating easy returns at the end of a product's life cycle are highlighted. Additionally, these initiatives aim to benefit society by generating employment, bolstering economic resilience, and serving as a mechanism for disaster resilience.

In the aeronautical industry, interviews from our research indicate that organizational policies are aligned with sustainability due to regulatory requirements rather than being specifically related to the pandemic. See the following comment:

"We were already focused on policies aligned with sustainability before the pandemic. Airlines are held accountable for their pollutant emissions, and our products are directly related to this, as they are the most significant emitters. Therefore, improving efficiency concerning emissions—that is, achieving more results with less fuel—is an inherent priority of the company. I don't see a significant change in this period, as we have always paid close attention to these environmental issues. For instance, 95% of the company's emissions come from aircraft usage, while only 5% relate to internal processes. Consequently, the focus is on exploring alternatives and renewable fuels that align with environmental policies and regulations.” (practitioner A)

“The pandemic has significantly impacted the aviation sector, which heavily relies on travel and the entire logistics of moving people and goods. However, the industry has been mobilizing not only to recover pre-pandemic levels but also has committed to carbon neutrality. Have you heard of the CORSIA? It's a global initiative created to achieve carbon-neutral growth in the international aviation sector. It establishes a carbon market to ensure that commercial flights between countries comply with carbon offset requirements in nations participating in the system. This involves the use of sustainable aviation fuels, although the current supply of these fuels is limited, and the utilization of carbon credits for offsetting purposes.” (practitioner Q)

Concerning the discussion about sustainability aspects transformations during the COVID-19 crisis, we develop the following proposition:

Proposition 6: The aeronautical sector, as a CAS, must adhere to norms, schema and realign visions and objectives with societal expectations and sustainability policies in the post-pandemic era, positively impacting the future of both humanity and the planet.

4.5 CONCLUSION

Concerning the literature of operations management, our results contribute as follows. During the COVID-19 period, research reported the pandemic's impacts on OSCM, but our research takes a different approach from previous studies. We conducted a systematic literature review (SLR) to identify emerging themes during the pandemic in operations management and discussed these themes with 17 practitioners from the aeronautical industry to report the key learnings throughout this process, the major changes that operations experienced, the management approaches that helped organizations navigate the crisis resiliently, and finally, we present the results highlighting insights on the legacy of COVID-19 for operations management. The main findings of the research are the confirmation that Industry 4.0 and digital transformation allowed organizations to maintain efficiency during the crisis; supply chain aspects such as resilience, integration, and localization have taken on a central role in organizational strategy; business models have undergone transformations and remote work remains a reality for most operations; innovation and agile strategies have enabled organizations to adapt to emerging demands; Lean Manufacturing has proven fundamental to resilience in times of crisis; and policies aligned with sustainability and social responsibility have strengthened in the face of the crisis. To the best of our knowledge, this is the first study presenting the legacy of COVID-19 for operations management and discussing these aspects with insights from practitioners in the aeronautical industry.

Its primary practical contribution lies in its thorough discussion of the legacy of COVID-19 on operations management. The research provides concrete insights and strategic recommendations that industry practitioners can use to boost resilience, efficiency, and adaptability in their operations and operational strategies for the future. Despite its contributions, this research also has limitations. Concerning the systematic literature review, although we aimed for comprehensiveness, some references may have been overlooked. Additionally, the semi-structured interviews provide insights based on the opinions of practitioners from the aeronautical industry. Although care was taken to select appropriate participants, the findings are based on personal perspectives. Therefore, future research should validate the proposed COVID-19 legacy through large-scale studies and explore their applicability across different industries and sectors.

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Appendix A - Classification of selected papers

Author	Year	Method	Publication	Main contribution
Adžić and Al-Mansour	2020	Survey	Management Science Letters	The paper presents a research scale that can be used to analyze the impact of COVID-19 on business.
Akpan, Soopramanien and Kwak	2020	Literature Review	Journal of Small Business & Entrepreneurship	The paper identifies the technologies, evaluates disruptive software platforms, and strategies needed for creating and managing small business innovation.
Akpan, Udoh and Adebisi	2020	Literature Review	Journal of Small Business & Entrepreneurship	The paper evaluates the implementation and use of state-of-the-art technologies by SMEs in EMDEs to improve operations performance and create sustainable competitive advantages
Al-Mansour and Al-Ajmi	2020	Literature Review	Journal of Asian Finance, Economics, and Business	The paper reports some of the major implications of COVID-19 on global business and strategy
Almeida, Santos and Monteiro	2020	Literature Review	IEEE Engineering Management Review	The paper analyzes the impact of digital transformation processes in three business areas: labor and social relations, marketing and sales, and technology

Author	Year	Method	Publication	Main contribution
Amoah, Khan and Wood,	2020	Literature Review	European Management Journal	Drawing insights from the current literature on business failure and the unfolding event of COVID-19, the paper highlights the paradoxes posed by novel exogenous shocks and the implications for SMEs.
Ahlqvist, Norrman and Jahre	2020	Literature Review	Operations and Supply Chain Management	The paper presents the term supply chain risk governance with an associated conceptual framework that embraces various types of supply chains and actors.
Atkinson et al.	2020	Literature Review	American Review of Public Administration	The paper analyzes the public failures that provide a deeper understanding of the U.S. government’s COVID-19 response’s impact on supply chains.
Barreiro-Gen, Lozano and Zafar	2020	Survey	Sustainability	The paper analyses how the outbreak has affected organizations’ sustainability priorities
Bartik et al.	2020	Survey	Proceedings of the National Academy of Sciences	The paper explores the impact of coronavirus disease 2019 (COVID-19) on small businesses.

Author	Year	Method	Publication	Main contribution
Bond et al.	2020	Literature Review	Journal of Service Research	The paper presents goods-centered companies' recent foray into the solution business and the pressing managerial questions regarding the evolution of solutions as the world begins to emerge from the COVID-19 pandemic.
Bretas and Alon	2020	Case study	Global Business and Organizational Excellence	The paper reveals how the COVID-19 outbreak has affected the franchising sector.
Baz and Rue	2020	Survey	International Journal of Production Economics	The paper investigates the role of supply chain risk management (SCRM) in mitigating the effects of disruptions impacts on supply chain resilience and robustness in the context of the COVID-19 outbreak.
Burgess and Connell	2020	Literature Review	The Economic and Labour Relations Review	The paper presents potential challenges and opportunities associated with the Fourth Industrial Revolution technologies and potential impacts on work and workplaces.
Cai and Luo	2020	Literature Review	Journal of Shanghai Jiaotong University (Science)	The paper studies the initial impact caused by the worldwide spread of the

Author	Year	Method	Publication	Main contribution
				coronavirus, such as production disruption of raw material and spare parts, unsatisfied market demand due to setbacks in logistics, increasing bankruptcy risk for small and medium-sized enterprises (SMEs), and demand fluctuation enlarge
Chenarides, Manfredo and Richards	2021	Modeling and Simulation	Applied Economic Perspectives and Policy	The paper shows that the pandemic revealed a fundamental lack of resilience in the food supply chain.
Chowdhury et al.	2020	Case study	Operations Management Research	The paper examines both impacts of the pandemic on the food and beverage industry.
Coveri et al.	2020	Literature Review	Journal of Industrial and Business Economics	The paper illustrates the mechanisms through which the COVID-19 pandemic affected GVCs in the context of a changing configuration of the global economy.
Craighead et al.	2020	Literature Review	Decision Sciences	The paper offers an agenda for supply chain management research on pandemics by considering how the key tenets of well-known and emergent theories can illuminate

Author	Year	Method	Publication	Main contribution
				challenges and potential solutions
Das and Patnaik	2020	Modeling and Simulation	International Journal of Electrical Engineering and Technology	The paper presents the impact of COVID-19 in various sectors considering the data which are secondary in nature
Derevyankina and Yankovskaya	2020	Literature Review	International Journal of Supply Chain Management	The paper presents the potential consequences of coronavirus for the presentation and disclosure of information in financial statements by economic entities.
Donthu and Gustafsson	2020	Literature Review	Journal of business research	The paper presents a global effort to address some of the pandemic-related issues affecting society.
Dwivedi et al.	2020	Literature Review	International Journal of Information Management	The paper presents a collective insight into many of the key issues and underlying complexities affecting organizations and society from COVID-19, through an information system and technological perspective.
Esper	2021	Literature Review	Journal of Public Policy & Marketing	The paper presents the COVID-19 outbreak impact in SCM.

Author	Year	Method	Publication	Main contribution
Fenwick, McCahery and Vermeulen	2020	Literature Review	European Business Organization Law Review	The paper presents lessons that can be learned from the COVID-19 outbreak.
Ferrannini et al.	2021	Literature Review	World Development	The paper presents a turning point in the connection between industrial policy, sustainability, and development that has been reached, highlighting the need to rethink its theoretical foundations as well as its governance and implementation processes for a new role in our post-Covid 19 societies.
Fonseca and Azevedo	2020	Literature Review	Management & Marketing: Challenges for the Knowledge Society	The paper reflects on the possible impacts of the Coronavirus crisis on the global supply chains and provide some recommendations to overcome the present situation
Free and Hecimovic	2021	Case study	Accounting, Auditing & Accountability Journal	The paper explores the underlying drivers of the supply chain vulnerability exposed by COVID-19 and considers potential future directions for global supply
Grida, Mohamed and Zaied	2020	Literature Review, BWM and TOPSIS	Transportation Research Interdisciplinary Perspectives	The paper provides an accurate study of the impact of the measures taken to

Author	Year	Method	Publication	Main contribution
				limit the spread of the epidemic and proposed a framework that evaluates the impact of the policies on the supply chain.
Gurbuz and Ozkan	2020	Survey	IEEE Engineering Management Review	The paper informs managers, decision-makers, and team leaders about the changes they will face in the post-Covid-19 world
Handfield, Graham and Burns	2020	Case study	International Journal of Operations & Production Management	The paper develops two case studies and provides the first insight from two senior VPs from two leading multi-national corporations tha were disrupted by COVID-19.
Harris et al.	2020	Literature Review	Local Economy	The paper approaches the COVID-19 crisis in the UK manufacturing ecosystem.
Hakovirta and Denuwara	2020	Literature Review	Sustainability	The paper redefines the concept of sustainability due to COVID-19 outbreak
He et al. (a)	2020	Modeling and Simulation	Emerging Markets Finance and Trade	The paper uses an event study approach to empirically study the market performance and response trends of Chinese industries to the COVID-19 pandemic.

Author	Year	Method	Publication	Main contribution
He et al. (b)	2020	Case study	Emerging Markets Finance and Trade	The paper adopts the financial data of Listed companies in China and uses the synthetic index compilation method to compile an accounting index that captures the period before and after the COVID-19 outbreak.
He and Harris	2020	Literature Review	Journal of Business Research	The paper argues that the Covid-19 pandemic offers a great opportunity for businesses to shift towards more genuine and contribute to addressing urgent global social and environmental challenges.
Herath, T. and Herath, H	2020	Literature Review	Information Systems Management	The paper discusses technology management and information systems in the COVID-19 era.
Hilmola et al.	2020	Survey	Sustainability (Switzerland)	The paper presents the COVID-19 implications for manufacturing and logistics.
Ibn-Mohammed et al.	2020	Literature Review	Resources, Conservation, and Recycling	The paper presents a critical review of the catalog of negative and positive impacts of the pandemic and proffers perspectives on how it can be leveraged to steer towards a better, more resilient

Author	Year	Method	Publication	Main contribution
				low-carbon economy.
Ikram et al.	2020	Literature Review and Fuzzy Delphi	Sustainability (Switzerland)	The paper presents the COVID-19 pandemic as an essential category and social sustainability attribute of corporate sustainable business practices
Ishida	2020	Case study	IEEE Engineering Management Review	The paper draws out some perspectives on the management of product supply chains in the event of a pandemic through cases specific to certain industries: automotive equipment, personal computers (PCs), and home furnishings.
Ivanov	2020a	Modeling and Simulation	Transportation Research	The paper presents the results of a simulation study that opens some new research tensions on the impact of COVID-19 on the global SCs.
Ivanov (b)	2020	Modeling and Simulation	Annals of Operations Research	The paper theorizes a new notion about the viable supply chain (VSC).
Ivanov and Das	2020	Modeling and Simulation	International Journal of Integrated Supply Management	The paper models the ripple effect of an epidemic outbreak in global SCs
Ivanov and Dolgui (a)	2020	Modeling and Simulation	International Journal of	The paper introduces a new angle in SC

Author	Year	Method	Publication	Main contribution
			Production Research	resilience research when resistance to extraordinary disruptions needs to be considered at the scale of viability
Ivanov and Dolgui (b)	2020	Modeling and Simulation	Production Planning & Control	The paper explores the conditions surrounding the design and implementation of digital twins when managing disruption risks in SCs
Ivanov and Dolgui (c)	2020	Literature Review	International Journal of Production Economics	The paper conceptualizes the current state and future research directions on the ripple effect for the pandemic context.
Juergensen, Guimón and Narula	2020	Literature Review	Journal of Industrial and Business Economics	The paper presents how the COVID-19 pandemic has challenged European small- and medium-sized enterprises (SMEs) in the manufacturing sector
Karmaker et al.	2021	TISM and MICMAC	Sustainable Production and Consumption	The paper investigates the drivers of a sustainable supply chain (SSC) to tackle supply chain disruptions in a pandemic context.
Khurana et al.	2021	Analytical Hierarchy Process (AHP)	Journal of Cleaner Production	The paper highlighted essential factors which can help companies to overcome the COVID-19 crisis

Author	Year	Method	Publication	Main contribution
				and other types of crises, by learning from the approaches taken in India.
Kraus et al.	2020	Case study	International Journal of Entrepreneurial Behaviour and Research	The paper presents an empirical study on the effects of the COVID-19 crisis on family firms allowing initial conclusions to be drawn about family firm crisis management.
Kuckertz et al.	2020	Case study	Journal of Business Venturing Insights	The paper presents interviews from an entrepreneurial ecosystem and offer a first-hand account of the adversity startups face during the COVID-19 crisis.
Kudyba	2020	Literature Review	Information Systems Management	The paper leverages existing research, and input from firms in various industries to illustrate technol-ogy-based issues including elements of the future of work that are transpiring in organizations as they adapt to this disruptive environment.
Lee, Lampel and Shapira	2020	Literature Review	Organization Science	The paper stocks the research on organizational learning from crises, and summarize useful knowledge for managing the COVID-19 crisis.

Author	Year	Method	Publication	Main contribution
Li et al.	2020	Modeling and Simulation	Chinese Journal of Mechanical Engineering (English Edition)	The paper develops a novel intelligent manufacturing framework for production recovery during the pandemic and builds an assessment model to evaluate the impacts of the technologies on industrial networks.
Liu, M. Lee and C. Lee	2020	Literature Review	Asian Business and Management	The paper presents the importance of resilience, strategic agility, and entrepreneurship in the context of the fight against COVID-19.
Lu et al.	2020	Survey	Environmental Hazards	The paper presents a survey with 4807 SMEs in Sichuan to assess the challenges associated with work resumption and the associated policy requirements in the COVID-19 era.
Marzantowicz, Nowicka and Jedliński	2020	Survey	LogForum	The paper identifies supply chain resilience in terms of risk management during the beginning of the COVID-19 pandemic spread in 2020.

Author	Year	Method	Publication	Main contribution
Mofijur et al.	2020	Literature Review	Sustainable Production and Consumption	The paper provides a comprehensive analysis of the impact of the COVID-19 outbreak on the ecological domain, the energy sector, society, and the economy and investigate the global preventive measures taken to reduce the transmission of COVID-19.
Mollenkopf, Ozanne and Stolze	2020	Literature Review	Journal of Service Management	The paper employs a transformative service lens to examine the role of the supply chain ecosystem in ensuring the health and safety of employees and customers as a well-being outcome during the coronavirus disease.
Monostori and Váncza	2020	Literature Review	Smart and Sustainable Manufacturing Systems	The paper gives a short assessment of the praiseworthy reactions of the manufacturing industry, which prevented society from sinking into an even deeper crisis
Nandi et al.	2020	Literature Review	Sustainable Production and Consumption	The paper provides insights from the COVID-19 pandemic for making supply chains more resilient, transparent, and sustainable.

Author	Year	Method	Publication	Main contribution
Niewiadomski	2020	Literature Review	LogForum	The paper proposes a procedure and a tool to identify key capabilities that determine the survival of enterprises in COVID-19 crisis conditions.
Okorie et al.	2020	Survey	IEEE Engineering Management Review	The paper identifies the barriers and enablers of manufacturing resilience, especially with regard to pivoting the manufacturing sector in response to the COVID-19 pandemic.
Paul and Chowdhury (a)	2020	Modeling and Simulation	International Journal of Physical Distribution and Logistics Management	The paper presents a mathematical model to develop a production recovery for a high-demand and essential item during COVID-19.
Paul and Chowdhury (b)	2020	Modeling and Simulation	Global Journal of Flexible Systems Management	The paper proposes some strategies to improve service levels during an extraordinary pandemic outbreak, such as COVID-19, for the most wanted products such as toilet paper.
Queiroz et al.	2020	Literature Review	Annals of Operations Research	The paper presents a systematic analysis of the impacts of epidemic outbreaks on SCs.

Author	Year	Method	Publication	Main contribution
Rapaccini et al.	2020	Survey	Industrial Marketing Management	The paper highlights major COVID-19 effects on both product and service businesses, including the disruption of field-service operations and supply networks.
Rashad and Nedelko	2020	Literature Review/interviews	Sustainability (Switzerland)	The paper develops a framework for the utilization of lean, agile, and leagile strategies in supply chains.
Ravindran and Boh	2020	Case study	IEEE Engineering Management Review	The paper presents five select cases of small and medium-sized enterprises (SMEs) and highlights the unique challenges faced by each of them as they pass through the COVID-19 crisis.
Rejeb A., Rejeb K. and Keogh	2020	Literature Review	Logforum	The paper presents a critical review of the literature to explore the impact of COVID-19 on the food supply chain.
Remko van Hoek	2020	Literature Review/interviews	International Journal of Operations and Production Management	The paper suggests a pathway for closing the gap between supply chain resilience research and efforts in industry to develop a more resilient supply chain.

Author	Year	Method	Publication	Main contribution
Robles	2020	Case study	IEEE Engineering Management Review	The paper analyzes five organizations that achieved radical transformation during COVID-19
Salimi, Sampaio and Golmaryami	2020	Literature Review	International Conference on Quality Engineering and Management	In the paper, the implication of the pandemic situation (COVID-19) is investigated for SCQM.
Schaltegger	2020	Literature Review	Sustainability Accounting, Management, and Policy Journal	The paper identifies sustainability learnings from origins of epidemics such as COVID-19 and deducts conclusions for businesses to create sustainable futures
Seetharaman	2020	Literature Review	International Journal of Information Management	The paper proposes a framework to analyze and examine the strategic shift effected by firms in specific industries.
Sharma, Adhikary and Borah	2020	Data analysis	Journal of Business Research	The paper offers strategic insights in terms of major issues firms are facing and strategic options firms are contemplating in COVID-19 era.
Sharma et al.	2020a	Stepwise Weight Assessment Ratio Analysis (SWARA)	International Journal of Logistics Research and Applications	The paper assists in understanding the key factors that need to be considered for maintaining an effective buyer–supplier relationship for

Author	Year	Method	Publication	Main contribution
				enhancing the survivability of SSCs in the COVID-19 era.
Sharma et al.	2020b	Fuzzy Linguistic Quantifier Order Weighted Aggregation (FLQ- OWA)	International Journal of Logistics Research and Applications	The paper identified and assessed the agricultural supply chain (ASC) risks caused by COVID-19 disruption.
Singh et al.	2020	Modeling and Simulation	International Journal of Production Research	The paper proposes a simulation model to help in developing a resilient and responsive food supply chain.
Siriwardhana et al.	2020	Literature Review	IEEE Engineering Management Review	The paper presents how 5G and Internet of Things (IoT) related technologies can be efficiently utilized and developed to fight against the COVID-19 pandemic.
Sjoberg	2020	Literature Review	IEEE Vehicular Technology Magazine	The paper analyzes how the COVID-19 pandemic has impacted the automotive industry and discusses the challenges companies that manufacture and sell automobiles face both in the short and long term.
Tortorella et al.	2020	Survey	Journal of Service Theory and Practice	The paper aims at examining the impact that the COVID-19 pandemic and its

Author	Year	Method	Publication	Main contribution
				related work implications have on the relationship between lean implementation and service performance.
Tripathi and Bagga	2020	Literature Review	Indian Journal of Economics and Business	The paper discusses the factors contributing to an organization's business continuity plan, including the adoption of Analytics and BI solutions in the COVID-19 era.
Trybula and Newberry	2020	Literature Review	IEEE Engineering Management Review	The paper provides thoughts on the means to move forward quickly to reestablish proficiency and regain former capabilities in a post-COVID-19 world.
Turnea et al.	2020	Survey	Sustainability (Switzerland)	The paper describes the relationship between low demand, cash flow problems, employee dismissals, and temporary leaves experienced by Romanian companies during the economic lockdown in the first two months of the COVID-19 pandemic
Varbanov, Jia and Lim	2021	Literature Review	Journal of Cleaner Production	The paper analyzes the main resource and pollution issues world-wide in

Author	Year	Method	Publication	Main contribution
				light of the current COVID-19 pandemic.
Veselovská	2020	Survey	Problems and Perspectives in Management	The papers assess the initial response undertaken by Central European companies in the early stages of the COVID-19 outbreak.
Xu et al.	2020	Literature Review	IEEE Engineering Management Review	The paper aims to investigate the COVID-19 impacts on the effectiveness and responsiveness of Global Supply Chains (GSCs).
Yallop and Aliasghar	2020	Literature Review	Online Information Review	The paper presents the transformative changes organizations experience, in the form of increased use of emergent information and communication technologies during the COVID-19 pandemic.
Zhu, Chou and Tsai	2020	Literature Review	Sustainability (Switzerland)	The paper addresses the relationship between supply chain operations and the ongoing COVID-19 pandemic.

CHAPTER 5 CONCLUSIONS

In this chapter, the conclusions from the results are presented. This encompasses the theoretical contributions and the practical implications derived from the outcomes of the survey, SLR, and semi-structured interviews featured in the three articles that comprise this thesis. Furthermore, the chapter discusses the study's limitations and potential future research to advance the state of the art.

The main goal of the thesis is to study operations management during a major disruption in supply chains during the COVID-19 pandemic. The first two articles in this thesis explored how organizations that adopted Lean Manufacturing and Industry 4.0 were affected by the pandemic, as well as the interface of these approaches with supply chain resilience. The third article of the thesis provides an overview of how operations management evolved throughout the pandemic period, highlighting the aspects of operations management that changed and continue to transform in a post-COVID-19 world. Specific topics can only be studied during a unique moment in history, such as the one presented in this thesis, underscoring the novelty and importance of the results achieved during this work.

To achieve the proposed objective, this thesis followed established research methods from the literature, which provided robustness and reliability to the scientific research conducted.

5.1 THEORETICAL CONTRIBUTIONS AND PRACTICAL IMPLICATIONS

This study provided several contributions to both the theoretical development of the subject and the guidance of leaders in organizations that have adopted Lean Manufacturing and Industry 4.0, and who seek to establish strategies aligned with supply chain resilience.

This thesis contributes to Lean Manufacturing (LM) literature when shows that Lean companies are responsive during periods of crises. Despite some criticisms of JIT regarding low stock levels during the pandemic, the research asserts that operational excellence achieved through LM was crucial for companies to navigate the challenges posed by COVID-19. This thesis contributes to operations management theory by highlighting the role of LM in aiding manufacturing industries in overcoming the effects of the pandemic on operations. The research confirms that adopting LM practices leads to favorable outcomes, improving companies' competitiveness and resilience in facing future challenges related to the pandemic. Regarding managerial implications, this study presents Lean Manufacturing (LM) as a philosophy for companies that extends beyond continuous improvement. When effectively implemented, it equips companies with the necessary tools to overcome future crises and disruptions, enhancing their responsiveness. Our research offers guidance to managers committed to resilience by demonstrating which LM practices are correlated with responsiveness. Additionally, the results suggest that lean practices helped companies navigate the COVID-19 outbreak more efficiently due to an organizational culture open to change and innovation.

This thesis contributes to Industry 4.0 literature when it investigates the impact of I4.0 technologies on smart manufacturing practices during times of crisis, particularly focusing on the Brazilian industrial sector. The research supports the notion that I4.0 adoption consolidates smart manufacturing practices, enhancing the development of smart capabilities and positively affecting performance. The results show the association between I4.0 technologies and smart manufacturing practices, shedding light on manufacturing companies' resilience during the pandemic. Regarding managerial implications, this research introduces engineers and managers to the technologies, practices, and smart capabilities linked to developing resilience strategies. As a result, it could be a guide for managers aiming to enhance their company's resilience. Managers can concentrate on I4.0 aspects that have been scientifically validated to support resilience practices.

This thesis contributes to operations management literature when presenting insights about the legacy of COVID-19 on OSCM. The study addresses emerging themes in operations management during the pandemic and interviews 17 practitioners from the aeronautical industry to discuss key learnings, major changes in operations, and management approaches that helped organizations navigate the crisis resiliently. The study highlighted that Industry 4.0 and digital transformation allowed organizations to maintain efficiency during the crisis. It emphasizes the central role of supply chain resilience, integration, and localization in organizational strategy, as well as the transformation of business models and the persistence of remote work in most operations. Additionally, innovation and agile strategies enabled organizations to adapt to emerging demands, Lean Manufacturing proved essential for resilience during the crisis, and sustainability and social responsibility policies were strengthened. Regarding managerial implications, this study offers valuable insights that can guide industry practices to overcome future crises.

5.2 LIMITATIONS AND FUTURE RESEARCH

Despite its contributions, this thesis has some limitations. In the quantitative research, the questionnaire gathered information from various industrial sectors and organizational levels. However, some data may be limited to senior managers within organizations, leading to instances where responses are based on a global perspective of the respondent's workplace.

Therefore, future studies should consider collecting data only from managers or directors. Additionally, while this research encompassed industries across multiple sectors, focusing on a specific manufacturing industry in future research may provide more nuanced insights, as the impact of the COVID-19 pandemic likely varied across different market segments. In the qualitative research, the semi-structured interviews offer insights based on the opinions of practitioners from the aeronautical industry. Although careful selection was made to choose suitable participants, the findings reflect personal perspectives. As such, future research should validate the proposed COVID-19 legacy through large-scale studies and examine its applicability across a variety of industries and sectors.

APPENDIX A - CONTRIBUTION OF AUTHORS TO THE ARTICLES

Article title	Authors	Contributions
Companies' responsiveness in facing supply chain breakdowns: the role of lean manufacturing	Débora Bianco	Main author of the article. Contributed to all stages of research, writing, literature review, data collection, data analysis, and discussion of results.
	Moacir Godinho Filho	Research coordinator. Contributed by leading and assisting the main author throughout the development of the article.
	Léony Luis Lopes Negrão	Contributed to the article by assisting the main author with data collection and statistical analysis.
	Gilberto Miller Devós Ganga	Contributed to the article by helping the main author build the theoretical foundation of the research.
	Guilherme Luz Tortorella	Contributed to the article by helping the main author build the theoretical foundation of the research.
	Jonhatan Magno Norte da Silva	Contributed to the article by assisting the main author with statistical analysis.
	Luana Bonome Message Costa	Contributed to the article by assisting the main author during data collection.
	Mariana Pereira Carneiro Barata	Contributed to the article by assisting the main author during data collection.

Article title	Authors	Contributions
The role of industry 4.0 in developing resilience for manufacturing companies during COVID-19	Débora Bianco	Main author of the article. Contributed to all stages of research, writing, literature review, data collection, data analysis, and discussion of results.
	Adauto Bueno	Contributed to the article by assisting the main author with data collection and theoretical foundation.
	Moacir Godinho Filho	Research coordinator. Contributed by leading and assisting the main author throughout the development of the article
	Hengky Latan	Contributed to the article by assisting the main author with statistical analysis.
	Gilberto Miller Devós Ganga	Contributed to the article by helping the main author build the theoretical foundation of the research.
	Alejandro G Frank, Charbel	Contributed to the article by helping the main author build the theoretical foundation of the research.
	Charbel Jose Chiappetta Jabbour	Contributed to the article by helping the main author build the theoretical foundation of the research.
The legacy of COVID-19 to operations management: systematic literature review and insights from industry	Débora Bianco	Main author of the article. Contributed to all stages of research, writing, literature review, data collection, data analysis, and discussion of results.
	Moacir Godinho Filho	Research coordinator. Contributed by leading and assisting the main author throughout the development of the article
	Adauto Bueno	Contributed to the article by assisting the main author with data collection and theoretical foundation.