THE IMPACT OF THE COVID-19 PANDEMIC DISRUPTION ON SUPPLY CHAIN PERFORMANCE IN THE ENGINEERING MANUFACTURING SECTOR

أثر الاضطرابات خلال جائحة كوفيد-19 على أداء سلسلة التوريد في قطاع التصنيع الهندسي

by

MARIAM YACOUB ALMAHARMEH

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ABSTRACT

Supply chain disruptions are common during unexpected occurrences, such as pandemics. The COVID-19 pandemic caused major supply chain disruption in the engineering manufacturing sector. Therefore, this dissertation aims to investigate the impact of the COVID-19 pandemic disruption on supply chain in the engineering manufacturing sector, and subsequent impact on effective process performance, particularly cycle times, production flexibility, and cost efficiency. Current research indicates that disruptions in the supply chain during the pandemic may include aspects such as raw material shortages, labour shortages, demand fluctuations, Communication or communication issues, among others, which in turn impact process outcomes in organizations. Additionally, literature advocates for the adoption of novel technologies, such as Industry 4.0, AI, and additive manufacturing to help ease the impact on firms. This study employed a quantitative research design, whereby a standardized questionnaire was distributed electronically to approximately 700 employees, affiliated to the firm being studied, in conformance to the current COVID-19 restrictions and regulations. 500 respondent questionnaires were selected, cleaned, entered, and analysed using IBM SPSS v.23. Pearson correlations were run between the study's dependent variables (Cycle Times, Production Flexibility, and Cost Efficiency) and the independent variables (Raw Material Shortages and Communication). The correlation results highlighted both negative and positive coefficients for the three primary variables, indicative of positive/constructive and inverse relationships. The study concluded that the effectiveness of management processes linked with these primary variables were significantly affected by the assessed supply chain disruptions during the COVID-19 period, which conforms with multiple research studies. This study further recommends the adoption of strategies that minimize such disruptions and bolster resilience during disaster periods, alongside revamped implementation of industry 4.0 technologies to fill in the gaps caused by supply chain disruptions during pandemics.

Key words: Supply chain; supply chain disruptions; COVID-19 pandemic; engineering manufacturing; risk assessment; risk management; analysis; exploratory factor analysis; correlations; industry 4.0; resilience

الملخص

تعد اضطرابات سلسلة التوريد من الظواهر الشائعة أثناء الحوادث و المخاطر غير المتوقعة، مثل الأوبئة. و بناء على ذلك يمكننا الاستنتاج أن جائحة كورونا قد تكون تسببت في اضطرابات كبيرة في سلسة التوريد في قطاع التصنيع الهندسي. لذلك تهدف هذه الأطروحة إلى التحقق من/استكشاف أثر الاضطرابات الناجمة عن جائحة كورونا على سلسلة التوريد في قطاع التصنيع الهندسي، وتأثيرها اللاحق على الأداء الفعال للعملية الإنتاجية لا سيما الأوقات المستهلكة خلال عملية الإنتاج (الفترات الزمنية لدورة الإنتاج)، و مرونة الإنتاج، و كفاءة التكلفة. تشير نتائج البحث في هذه الأطروحة إلى أن الاضطرابات في سلسلة التوريد أثناء الجائحة قد تشمل جوانب متعددة مثل نقص المواد الخام، نقص الأيدي العاملة، و تذبذب الطلب، والمشاكل المتعلقة بنقل المعرفة أو التواصل، إلى جانب أمور أخرى، والتي بدورها تؤثر على نتائج العملية الإنتاجية في الشركات و القطاعات الهندسية. بالإضافة إلى ذلك، تدعو أدبيات البحث المتضمنة في هذه الأطروحة إلى اعتماد تقنيات جديدة مثل الذكاء الاصطناعي و التصنيع الذكي (الصناعة 4.0)، والتصنيع المضاف (التصنيع ثلاثي الأبعاد) للمساعدة في تخفيف الأثار على الشركات الهندسية. استخدمت الدراسة في هذه الأطروحة تصميماً بحثياً كمياً، حيث تم توزيع استبيان معياري الكترونياً على ما يقارب 700 موظف و إداري تابع للشركة قيد الدراسة، بما يتوافق مع القيود و اللوائح الحالية الخاصة بكوفيد -19. تم تلقي 500 استبيان و الذي تم اختيارهم، وتنقيحهم ثم إدخالهم و تحليلهم باستخدام برنامج التحليل الاحصائي SPSS النسخة رقم 23 و المطورة من قبل شركة IBM. حيث تم استخدام التحليل العاملي الاستكشافي، و الترابطات بين المتغيرات التابعة (الفترات الزمنية لدورة الإنتاج، مرونة الإنتاج، و كفاءة التكلفة) و المتغيرات المستقلة (نقص المواد الخام، ومشاكل التواصل) للدراسة. أظهرت نتائج الارتباطات كلا من المعاملات السلبية و الإيجابية للمتغيرات الأساسية الثلاثة، مما يدل على العلاقات الإيجابية/ البناءة و العكسية. خلُصَت الدراسة إلى أن فعالية/كفاءة عمليات الإدارة المرتبطة بهذه المتغيرات الأولية قد تأثرت بشكل كبير باضطرابات سلسلة التوريد التي تم تقييمها خلال فترة كوفيد-19، و الجدير بالذكر أن ما خلصت له هذه الدراسة يتوافق مع دراسات بحثية أخرى متعددة. كما توصي الدراسة الحالية باعتماد استراتيجيات تقلل من هذه الاضطرابات و تعزز المرونة أثناء الكوارث، إلى جانب التنفيذ المحسن لتقنيات التصنيع الذكي لسد الثغرات التي تسببها اضطرابات سلسلة التوريد أثناء الأوبئة و الأزمات.

الكلمات الأساسية: سلسلة التوريد، اضطرابات سلسلة التوريد، جائحة كوفيد-19، التصنيع الهندسي، تقييم المخاطر، إدارة المخاطر، التحليل، التحليل العاملي الاستكشافي، الارتباطات، التصنيع الذكي، المرونة

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LIST OF ABBREVIATIONS

SMEs	Small and Medium-Sized Enterprises
NAM	National Association of Manufacturers
WHO	World Health Organization
WTO	World Trade Organization
PPE	Personal Protective Equipment
IBM	International Business Machines Corporation
SPSS	Statistical Package for the Social Sciences
EFA	Exploratory Factor Analysis
KMO	Kaiser-Meyer-Olkin Test
CFA	Confirmatory Factor Analysis
GFC	Global Financial Crisis
GDP	Gross Domestic Product
GIS	Geographical Information Systems
SC	Supply Chain
SCM	Supply Chain Management
AM	Additive Manufacturing
EPQ	Economic Production Quantity
STV	Subject-to-Variable Ratio
PAF	Principal Axis Factoring
PCA	Principal Component Analysis
AI	Artificial Intelligence
IoT	Internet of Things

CHAPTER ONE: INTRODUCTION

1.1 Research Background

The coronavirus, or COVID-19 pandemic, is a severe health crisis with devastating impact on society. In particular, upon its onset, many countries worldwide rightly decided to close down businesses (especially that were highly susceptible to a coronavirus outbreak). The crisis exacerbated the dilemma policymakers faced between closing businesses to reduce contacts and save lives, and keeping these organizations open to sustain jobs and improve the economy (Burgess & Sievertsen, 2020). The pandemic has caused short-term instability in many industries around the world, whereby workforce shortages caused by lockdown impositions have made it difficult for firms to run their daily in-house operations smoothly (Shen, Yang & Gao, 2020). Businesses have moved their activities online; the majority of organizations are adopting enterprise resource management tools hosted in the cloud to better optimize their work, and enable their workers to operate remotely while having a comparable working environment as found in the office. Online conferencing and video streaming businesses have seen their net worth more than triple in months as more and more companies are continually adopting these tools for proper business engagement and integrations. Some regions, or nations, have been shut down while attempting to combat the coronavirus pandemic. These lockdowns shut down most manufacturing activities, with the exception of critical manufacturing, and caused major disruptions to global supply chains, as supply chain companies are internationally dispersed across countries (Shen, Yang & Gao 2020). Traditional supply chains are typically linear, so the integrity of the entire chain can be compromised by issues in a single connection (area shutdown or logistics congestion/blocking). As companies gradually resumed operations, due to travel limitations, labour shortages became a major problem. Owing to the lack of raw materials or parts from overseas nations, some manufacturers have had to stop production, while others have had to slow or halt production, because the goods produced cannot be transported overseas.

Numerous enterprises around the world were affected by various COVID-19-related disruptions, such as issues in their supply chains, multiple order cancellations, and other logistical/transport disruptions, whereby small and medium-sized enterprises (SMEs) were the hardest hit, despite them being the major contributors to regional and national economies (Shafi, Liu & Ren 2020). However, unlike bigger enterprises, the SMEs usually do not possess sufficient resources, especially financial and managerial, and are not prepared for such disruptions likely to go longer than expected, hence would be adversely impacted by a nationwide lockdown, this is why many governments have mapped out benefit funds to help sustain SMEs as they battle to curb the spread of the virus.

Disruptions in the global supply chain and other business operations, resulting from disasters, have led researchers and practitioners in management to refocus on the survivability of firms. Disasters, such as natural disasters caused by climate change, political insurgences, and most recently, epidemics, such as the coronavirus, cause significant shifts in supply chains that firms need to prepare for in advance. For example, the recent shift in the semiconductor manufacturing sector, to suit the growing more profitable demand for these technologies in consumer goods (such as laptops, tablets, televisions) driven by the widespread lockdown, has left a significant gap in the supply of semiconductors necessary for vehicle manufacturing, thereby causing costly supply chain disruptions in engineering/automotive manufacturing industries. Resultantly, firms will eventually develop innovative strategies for survival during, and after such extreme events. A possible framework/roadmap for ensuring firms achieve their objectives entails the transformation of their supply chain activities and operations to include reliable, agile, and transparent cyber-physical systems, mostly through approaches such as mechanization and digitalization

(Farooq et al., 2021). The primary problem is that most firms lack comprehensive strategies that can deter significant supply chain disruptions which adversely affects the smooth running of operations in manufacturing. Most manufacturers have recently been forced to close their manufacturing operations or drastically reduce production capacities. The logistical operations associated with maintaining the smooth running of supply chains are currently impacted by widespread government restrictions on movement (on goods and human resources). Thus, it is crucial to focus on imminent and actual supply chain disruptions and the various performance aspects linked with the engineering manufacturing sector during the coronavirus pandemic since this is an area of study with a significant research gap. Thus, the primary aim of the current study is to investigate the impact of the coronavirus pandemic on supply chain disruption in engineering manufacturing sector at an industry level.

The coronavirus pandemic has highlighted a multitude of challenges faced by manufacturers, whose majority of tasks cannot be conducted remotely based on the current healthcare requirements and restrictions. According to Sorensen and Bono (2021), approximately 80% of all manufacturing firms predicted that the calamity would have significant supply chain and financial impact on their activities. The National Association of Manufacturers (NAM) indicated that some of the primary supply chain disruptions that engineering manufacturers must contend with, include supply chain bottlenecks (for instance, in the case of the supply of semiconductor chips for the automotive industry), a surge in oil demand and price, plummeting spending patterns, and credit availability/affordability for both the producers and their suppliers (Sorensen & Bono 2021). Delving deeper into the supply chain, producers with globalized supply chains are increasingly recognizing that tier two and three suppliers are the most affected by the current pandemic-related disruptions. Therefore, there is also a significant knowledge gap regarding the various forms of disruption faced by lower tier suppliers that is escalating the supply chain disruptions, witnessed in the industry.

The Covid-19 pandemic has certainly affected the SME's, and it is a topic worthy of extensive research. Nevertheless, this project studies the impact of the pandemic on a larger scale, focusing on the engineering manufacturing sector. The manufacturing industry was significantly impacted by the pandemic, with disruptions being either external regarding supply chain instabilities, or internal in terms of interrupted demand-supply chains and entire production systems and processes. These disruptions have prompted scholars in different disciplines to critically research their effects. Researchers have closely examined different ways of handling the pandemic in the manufacturing sector by mass production of WHO-certified Personal Protective Equipment (PPE) and some other medical equipment (Prather, Wang & Schooley 2020; Kis et al. 2020). Some scholars examined Italian manufacturing firms in Sweden and Italy using a survey of 177 respondents, their aim was to assess the impact of the disruption caused by COVID-19 on product and services and thereafter create a crisis management model. Other researchers have evaluated the impact caused on the manufacturing industry by critically assessing it from the perspective of supply chain risk and resilience (Linton & Vakil 2020; Rapaccini et al. 2020). However, current research still lacks adequate research on the impact of the pandemic on the broader engineering manufacturing industry, particularly regarding aspects such as Communication through the supply chain, raw material shortages, cycle times, cost efficiency, and production flexibility, thereby indicating a research gap which the current study explores.

1.2 Research Significance

Based on the reviewed literature, the primary problem is that most firms lack comprehensive strategies that can deter significant supply chain disruptions which adversely affects the smooth running of operations in manufacturing. Most manufacturers have recently been forced to close their manufacturing operations or drastically reduce production capacities. Therefore, the significance of this research is to focus on imminent and actual supply chain disruptions and the various performance aspects linked with the engineering manufacturing sector during the coronavirus pandemic since this is an area of study with a significant research gap.

1.3 Research Problem Statement

The current research identifies one particular problem: the impact of the pandemic on supply chain disruption in the engineering manufacturing sector, which highlights a need to research the causal factors linked with this disruption. Going deeper into the supply chain, producers with globalized supply chains are increasingly recognizing that tier two and three suppliers are the most affected by the current pandemic-related disruptions. Therefore, there is also a significant knowledge gap regarding the various forms of disruption faced by lower tier suppliers that is escalating the industry-wide supply chain disruptions. Thus, this study addresses this knowledge gap by investigating the impact of COVID-19 in engineering organizations in the manufacturing industry, particularly the disruptions in the supply chain caused by raw material shortages and Communication, and how these disruptions impact performance or process effectiveness outcomes such as production flexibility, cost efficiency, and cycle times. This study's findings will help the management within the engineering manufacturing sector make evidence-based decisions and develop sufficient measures to address the pandemic's supply chain disruption issues and the associated performance problems.

1.4 Research Questions

This research seeks to answer two primary research questions:

i. Do the current disruptions in the supply chain, caused by the COVID-19 pandemic, including raw material shortages have a significant impact on the effective management process performance (cycle times, production flexibility, and cost efficiency) in the engineering manufacturing sector?
ii. Does Communication throughout the supply chain have a significant impact on the effective management process performance aimed at addressing the issues caused by supply disruptions (such as cycle times, production flexibility, and cost efficiency) in engineering manufacturing industry during the coronavirus pandemic?

1.5 Research Aims and Objectives

The research aims to investigate the impact of the coronavirus pandemic on supply chain disruptions in the engineering manufacturing sector, and their impact on effective process performance (as presented by dependent variables and sub-variables), including the role of the management during the pandemic. The approach is aimed at helping management in engineering manufacturing firms make evidence-based decisions when tackling or mitigating supply chain disruptions during disasters, and for improving or managing process effectiveness (cycle times, production flexibility, and cost efficiency) during disasters/pandemics with the consideration of various factors such as Communication throughout the supply chain and mitigating raw material shortages which represented the independent variables. The study will involve research on an engineering manufacturing firm since it espouses all aspects of a company in the sector. Aspects such as lockdowns, social distancing rules, border restrictions, and mortality rates will be considered to accurately describe the impact caused by the pandemic.

In order to achieve these aims, the investigator will address the following objectives:

i. To help management in engineering manufacturing firms make evidence-based decisions when tackling or mitigating supply chain disruptions during disasters/pandemics.
ii. To recommend ways of improving or managing process effectiveness (cycle times, production flexibility, and cost efficiency) during disasters/pandemics with the consideration of various factors such as Communication throughout the supply chain and mitigating raw material shortages.

1.6 Conceptual Framework and Hypotheses

1.6.1 Conceptual Framework

Figure 1 below illustrates the conceptual framework used by the study to develop the hypotheses. The framework highlights an interaction of variables during the coronavirus pandemic and their effect on engineering manufacturing, whereby the study will be conducted within an engineering manufacturing firm. This conceptual paradigm represents the study's primary idea and focus and will help the researcher comprehensively investigate the subject. The external factor, namely the pandemic environment, is characterized by aspects such as lockdowns, social distancing rules, border restrictions, and mortality rates, elements that will be used to properly describe the impact of coronavirus within the industry. The framework (Figure 1) illustrates the disruption in the supply chain which presented by two independent variables: Communication throughout the supply chain and raw material shortages, and the dependent variable which is process effectiveness, that is presented by the sub-dependent variables: cycle times, production flexibility, and cost efficiency. The effect of COVID-19 disruption was measured using the two independent parameters/variables, and this will be done through the dependent variables and the sub-dependent variables, in order to determine the correlation between the two sets of variables. Additionally, risk/disruption in supply chain was assessed through studying the likelihood and impact of each risk event on the process performance indicators tested using an ordinal scale of 1-5 to develop the questionnaire. To measure the variables, survey questions were answered by each respondent from the firm. Exploratory Factor Analysis (EFA), Correlations, using SPSS will be employed to conduct data analysis. Independent variables will be evaluated quantitatively as well as their effect on dependent variables.

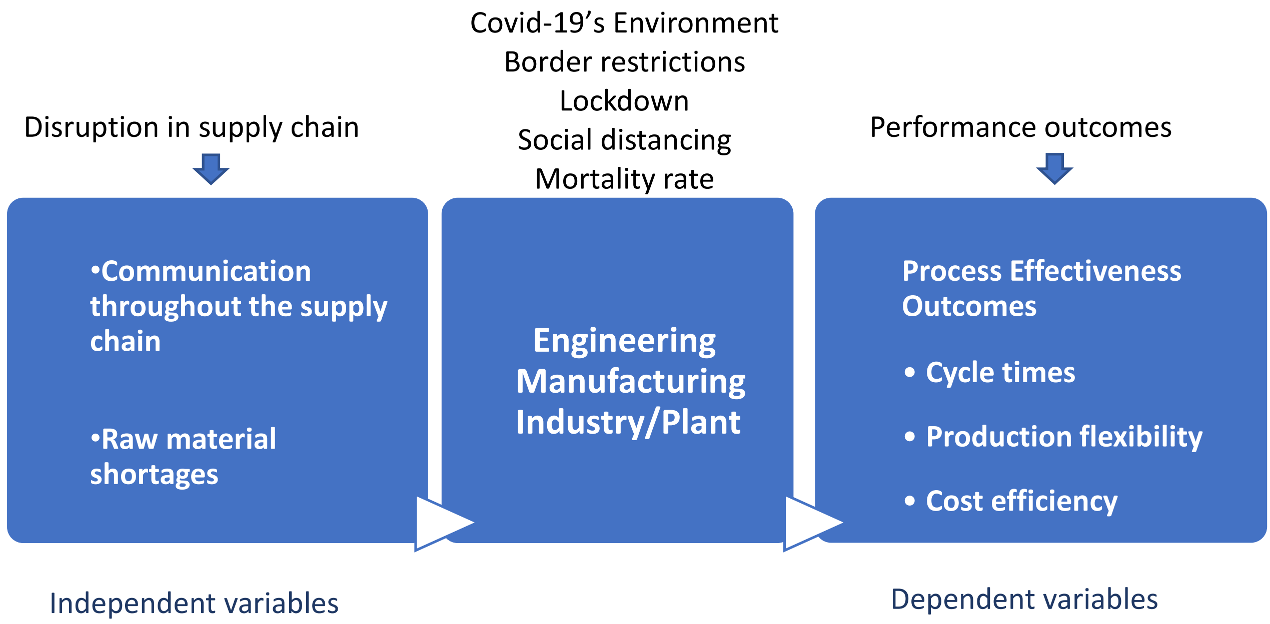

Figure 1 The Proposed Conceptual Framework for the Current Study

1.6.2 Research Hypotheses

This research aims at assessing the following hypothesis based on the outlined aims, objectives, and research questions:

i. The First Hypothesis: There is a significant relationship between COVID-19’s supply chain disruption aspects, particularly raw material shortages, and the processes effectiveness (cycle times, production flexibility, cost efficiency) in engineering manufacturing firms.

ii. The Second Hypothesis: There is a significant relationship between Communication throughout the supply chain and the process effectiveness outcomes (cycle times, production flexibility, and cost efficiency) in engineering manufacturing sector.

1.7 Organization of the Dissertation

This study is organised into five chapters. The first chapter covers the introduction, including a background of the study, problem statement and significance, research questions/aims/objectives, and the conceptual framework and hypotheses. Chapter 2 is a discourse on literature review, entailing recent research, publications, journals, and presentations or articles on various perspectives regarding how the coronavirus pandemic has impacted the manufacturing industry, with keen interest on the engineering manufacturing sector. Chapter 3 outlines the methodology used for data collection, entry, analysis, and presentation for discussion on the findings. The study employs a quantitative research design, whereby a standardized questionnaire will be distributed electronically to approximately 700 employees affiliated to the firm being studied, in conformance to the current COVID-19 restrictions and regulations. Chapter 4 entails a presentation of the analysed results. In addition, it also covers an in-depth discussion of the analysed results to develop enough justification of the research topic alongside revisiting the methodology and literature review to compare and contrast findings, establish study limitations, and determine possible future research gaps that have not been addressed by the study's contribution to current literature. Finally, Chapter 5 is the conclusion and recommendations section, whereby the author summarizes the key findings of the research while developing a final judgment based on the significance of the study findings; highlights the study's gaps or limitations, while placing the findings in the broader literature perspective; highlights the future scope of the work, including other studies that could be carried out; a discussion of the real-life or practical applications of the findings within the wider engineering manufacturing industry; and addressing possible criticisms that could be affiliated to the study.

CHAPTER TWO: LITERATURE REVIEW

2.1 Supply Chain Disruption Definition

Supply chain disruption may have multiple meanings based on the context of application. Generally, supply chain disruptions can be defined as the unforeseen aspects that interpose the procurement and delivery of crucial raw materials, which in turn impacts the operations and financial progress of an organization (Butt, 2021). Different studies focus on diverse aspects relating to supply chain disruption. For instance, Ellis, Henry and Shockley (2010) explicate the magnitude and probability of disruptions that impact supply chains, while Wamba (2020) investigated disruption severity. Additionally, Butt (2021) states that disruptions within the supply chain may spread throughout every aspect of the chain since such risks are often correlated, meaning that any interference on one aspect of the supply chain may significantly impact other downstream or upstream aspects within the production line in a manufacturing firm. Several studies have documented the potential risks regarding the disruption of supply chains in different industries, including port blockades and transportation delays, natural disasters and disasters/epidemics, quality issues and part shortages, jeopardized communication channels, disputes regarding labour, and operational issues (Chapman, Soosay & Kandampully, 2002; Chopra & Sodhi, 2004; Cooke and Rohleder, 2006; Craighead, Ketchen Jr & Darby, 2020; Machalaba & Kim, 2002). The researchers have also demonstrated the impact of severe and recurrent disruptions on the wider industry and individual organizations' performance levels in their supply chains. Wamba (2020) posits that the management of highly intertwined supply chain is a growing challenge in the current competitive business environment. The growing levels of supply and demand uncertainty, shortened product life cycles and technological efficacy, market globalization, and logistical and manufacturing partnerships have resulted in a highly complex global supply chain network which is highly vulnerable to major disruptions in the event of a catastrophe, natural disaster, or pandemic (such as COVID-19). With the growing complexities in the supply chain, there is a high level of interdependence between manufacturers and third-party stakeholders, such as logistical firms and the distributors of raw materials (Fan et al. 2019). Accordingly, studying these interdependencies and risk, and how they influence supply chain disruption and impact organizational/industry-wide performance is a major topic of interest for today's supply chain managers. Although heightened risk levels in the supply chain can result in significant challenges, studies have reported that firms which adopt higher flexibility levels have a better capacity at handling unforeseen events resulting in major supply chain disruptions, such as global pandemics, more successfully than their non-flexible competitors.

2.2 Supply Chain Pandemic Disruptions

Disruptions in supply chains are known to impact organizational performance significantly. For instance, incidents, such as the 2008 global financial crisis (GFC), the 2011 Tsunami, and, most recently, COVID-19, have extensively demonstrated how globally interconnected supply chains intensify even the smallest of disruptions (Nikolopoulos et al., 2021). Accordingly, researchers have attempted to expound on various aspects that are associated with resilient supply chains the organizational and network level (Bode et al., 2011; Kim, Chen & Linderman, 2015). The extent of the disruptions in manufacturing enterprises during the COVID-19 pandemic has challenged common knowledge on supply chain resilience. According to Nikolopoulos et al. (2021), the global pandemic has caused significant deterioration to various economic and business indicators, including the worldwide GDP and productivity levels. Additionally, research shows that the pandemic has reduced the labour demand by at least 16%, mostly caused by trade and travel impositions and restrictions, as well as workplaces that have been shut down indefinitely (Brinca, Duarte & Faria e Castro, 2020; Nikolopoulos et al., 2021). Resultantly, Araz et al. (2020) conclude that the coronavirus pandemic could be the worst supply chain disruption in the last ten years. Ivanov's (2020b) global supply chain simulation model offers a prediction for the stress caused by the pandemic on hospital infrastructure, thereby forecasting how the labour market for the manufacturing sector could be impacted with time. In brief, COVID-19 continues to strain the globalized supply chain for manufacturers and other industries in a highly complex and entwined manner. Current literature on supply chain disruption and prediction, offers some insights on how these complexities occur. Additionally, the literature highlights some core challenges linked with the identification and response to significant demand pattern changes especially in the manufacturing sector as the pandemic unfolds. Developing capacities to estimate shifts in demand and supply for both raw materials and end products could have major implications for policy makers and supply chain management, whereby the former could make use of the collected data to formulate evidence-based and practical sector-wide interventions (such as subsidizing highly-impacted supply chains and prioritizing the critical ones), while the latter would be more clearly informed regarding early warning on an imminent pandemic or catastrophe, and able to adjust key supply chain aspects/mechanisms accordingly to ensure resilience during such periods of change.

2.3 Engineering Manufacturing Sector Challenges

Most of those infected with the COVID-19 virus face moderate or mild respiratory ailments, depending on the strain and the geography, whereby a significant number are able make full recovery without the need for specialized treatment. However, not all countries have access to the right amount of protective equipment (masks and sanitizers) or vaccines, or even the right enforcement measures to help curb the spread of the virus, which further impacts the wider labour force (Butt, 2021). Recently, with the spread of new and deadlier COVID-19 strains, governments have been compelled to extend the lockdown and curfew periods, significantly impairing production activities in numerous manufacturing and logistics firms across the globe. According to Butt (2021), the impact of the pandemic has led to the development of stern measures such as export restrictions and trade barriers, which in turn adversely impact the worldwide credit and production sectors, which are foundational for the success of manufacturing firms. Additionally, the pandemic has significantly disparaged the foreign exchange market, alongside energy and commodity prices, which have a direct impact of a wide range of manufacturing aspects in different firms or sectors. The WTO (2020) projected a downfall of global trade ranging between 13% and 32% during the COVID-19 pandemic, because of the widespread disruption of regular economic activities worldwide. The impact of the pandemic also has a ripple effect in different supply chains across a wide range of manufacturers. Butt (2021) posits that the ripple effect caused by the coronavirus pandemic on global supply chains has never been experienced on such a scale before, since the current situation involves a widespread restriction of the movement of goods because of the instituted lockdown measures. Firms have to tolerate the low supply of key raw materials due to these restrictions, causing major logistical and supply chain challenges. The reduction in supply, coupled with substantially un-impacted demand levels ultimately results in significant price increases. Secondly, the pandemic has led to production cessation, causing a drastic drop in demand for various products. Thirdly, cash flow for distributors and manufacturers is also under stagnation, which could result in further economic slow-down since key suppliers do not have sufficient cash, except for those dealing with essentials. Fourth, the coronavirus pandemic has caused a widespread cessation of movement for labourers to curb the spread of the virus, meaning that core tasks in the manufacturing sector which cannot be handled remotely will be kept on hold for a while longer. Thus, the impact of the COVID-19 pandemic on the manufacturing sector is widespread.

The pandemic's impact on the supply sector is also overwhelming for the manufacturing sector. For example, according to Correia et al. (2020), the supply capacity of entire countries and sectors could be adversely affected by current restrictions, such as mobility restrictions, measures of self-isolation, and rising mortality rates with new virulent variants. Additionally, McKibbin and Fernado's (2021) study indicates that there was a drastic fall in the supply of labour, a significant growth in risk premiums, and rising costs of production in different manufacturing sectors as key effects of the COVID-19 pandemic.

Research indicates that the manufacturing sector has been among the hardest hit industries globally. Rapaccini et al.'s (2020) study investigated the impact of the pandemic on North Italian producers. This was after the spike in the confirmed coronavirus cases; the rising mortality rate caused by the virus; and the disruptive effect caused immediately the government responded to the outbreak by imposing radical lockdown measures, banning nonessential travel, and mandating the shutdown of all nonessential businesses. The authors reiterated that the adoption of automated production systems and suitable models of business to increase organizational resilience during such occasions.

In many developed nations, engineers are tasked with creating advanced solid waste collection systems using mathematical modelling and tools of geographical information systems (GIS). Sarkodie and Owusu (2020) studied how the containment of the global virus and the restrictions on mobility, business activities, and social distancing measures have affected solid waste collection and other waste management processes. They found from their research that the quantity of waste increased across countries observing stricter social distancing measure, such as staying at home (Sarkodie & Owusu, 2020). In the United Kingdom, engineering organizations in the manufacturing industry were greatly hit by the COVID-19 crisis and the ongoing recession especially at a Post-Brexit era when the nation's ecosystem has been in a worrying state. Harris et al. (2020) investigated how the national and local industrial strategies should respond to the ongoing COVID-19 crisis, especially as it concerns the manufacturing sector of engineering organizations.

In the global additive manufacturing industry, Kunovjanek and Wankmuller (2020) studied how engineering organizations in this sector are responding to the COVID-19 crisis, especially when there are global supply disruptions and shortages that have resulted in countries battling over desperately needed supplies, shifting manufacturing mostly towards the production of medical apparel (such as personal protective equipment - PPE) and equipment (such as ventilators). Kunovjanek and Wankmuller's (2020) study reviewed 289 additively manufactured products (AM products) produced in response to the pandemic. These events have led to major disruptions in the supply chains of virtually all manufacturers during COVID-19 pandemic. However, the extent of the impact is yet to be clearly assessed in most of the current studies. Biswas and Das (2020) studied the primary SCM barriers faced by Indian manufacturers. They found five essential aspects in supply chain management during the pandemic, including lack of transport, strict enforcement of local laws, lack of manpower, raw material scarcity, and cash flow deficiencies within the manufacturing industry during the lockdown period. Based on these outcomes, the authors proposed a methodology built on a fuzzy analytical hierarchy process (Fuzzy-AHP) to assess it.

Lockdowns shut down most manufacturing activities, with the exception of critical manufacturing, and caused major disruptions to global supply chains, as supply chain companies are internationally dispersed across countries (Shen, Yang & Gao, 2020). As companies gradually resumed operations, the imminent travel limitations and labour shortages became a major problem, mainly caused by the lack of raw materials, interruptions in distribution schedules, export cancellations, and the falling demand of nonessential commodities (Shafi, Liu & Ren, 2020). The manufacturing sector has been adversely disrupted by COVID-19, the scope of disruption has been largely twofold; an internal disruption of manufacturing processes and systems as well as drastic changes in demand and supply triggered by external instability in the supply chain. Various studies have investigated how engineering organizations in global additive manufacturing industry are responding to the COVID-19 crisis, especially at a time when there are global supply disruptions and shortages. The study by Kunovjanek & Wankmuller (2020) reviewed 289 additively manufactured products (AM products) manufactured in response to the pandemic. Other issues documented in the study included poor print quality, poor technology (advancement and adoption), and down-surging supply of key inputs.

Research indicates that the manufacturing sector (including engineering manufacturing) has been among the hardest hit industries globally caused by the COVID-19 pandemic. The outbreak has adversely impacted the smooth flow of manufacturing operations, with most manufacturers being forced to either operate at minimum capacity or fully close their production operations. The logistical operations associated with the fulfilment of supply and demand were significantly interrupted by aspects such as government restrictions and airport/port bans, thereby impacting the overall movement of raw materials and finished products. At the same time, there was an exponential rise in demand for medical apparel and equipment, which refocused most manufacturing production lines to upscale or prioritize such production in place of other engineering manufacturing products (Farooq et al., 2021). In the recent past, technological integration and strategic decision-making with the core aspects of supply chain management (SCM) and operations have been under study by multiple researchers globally, particularly regarding how epidemic outbreaks and other disasters impact local and global supply chains. Most of these studies focus on procurement and distribution, resource allocation, relief operations management, network design-oriented decision-making strategies, and emergency response

(Anparasan & Lejeune, 2018; Govindan, Mina & Alavi, 2020; Ivanov & Das, 2020; Preciado et al., 2013). Moreover, most of this research was conducted in support of influences caused by previous disasters and linked with operations management and supply chain networks (Anparasan & Lejeune, 2018; Dasaklis, Pappis & Rachaniotis, 2012; Duijzer, Van Jaarsveld & Dekker, 2018; Ivanov, 2020a; Ivanov & Dolgui, 2020b; Kumar & Havey, 2013; Pastor-Satorras et al., 2015). Thus, current literature highlights some prominent research gaps that need to be addressed regarding the impact of the current COVID-19 outbreak on global supply chains. China is among the world's biggest engineering manufacturing hubs worldwide, particularly in the electrical and electronics equipment production, vehicle and heavy machinery manufacturing, textiles, medical equipment and gadgetry, among other sectors (Farooq et al., 2021). The outbreak of the COVID-19 virus in China prompted a major disruption of key supply chains, both locally and globally. Two primary goals emerged from the disrupted supply chains, including managing operational and resource sustainability and shifting to digital-based production systems. Accordingly, Farooq et al. (2021) posits that the alignment of Industry 4.0 (i.e., automated manufacturing) could be up scaled as a foundation to effectively manage supply chains during pandemics such as COVID-19. However, the question remains about the system-level flexibility of most production lines, or entire firms towards efficiently and sustainably adopting automated systems to run most of their supply chain and manufacturing operations in the long-term.

The current supply chain (SC) challenges have prompted numerous debates regarding the robustness of previous SCM approaches, used during comparable disasters or epidemics (such as Ebola or the Spanish Flu). For example, frameworks such as agile and lean manufacturing were found to focus on sustainability and resilience aimed at growing market response levels during such incidents rather than fostering the survivability of enterprises (Dolgui, Ivanov & Sokolov, 2020; Ivanov, 2020b). Aspects regarding the viability and sustainability of SC network operations under varied conditions have also been re-assessed to evaluate the impact on supply chains under the current pandemic (Ivanov & Das, 2020; Ivanov & Dolgui, 2020a; Ivanov & Dolgui, 2020b). However, according to Culot et al., (2020), long-term solutions on SC sustainability during pandemics is based on the effectiveness of digital integration in the core logistical and manufacturing processes. Most firms in the engineering manufacturing sector are undergoing a major re-invention of their technological portfolios to upscale supply chain resilience and sustainability during the pandemic period, and in readiness for the future.

Previously, disruptions in the supply chain during outbreaks have caused significant threats to entire economies worldwide, while also impacting industrial sustainability and the overall well-being of the public, for example, the Spanish Flu which occurred in the 20th century. The primary reasons of these widespread impacts include poorly advanced technological systems for supporting remote business operation, inadequacy of key disease control and management systems, and the unreliability of supply chain networks (Farooq et al., 2021). Recently, decision science has developed advanced approaches to augment the sustainability of operations in disrupted environments, with the potential to apply the concepts extensively to disasters and epidemics, thereby minimizing impacts on supply chains and overall production outcomes. For example, the study of the allocation of resources in diverse environments (including remote areas) indicates a core area of exploration and application in manufacturing supply chains. Additionally, the adoption of technologies such as additive manufacturing and other Industry 4.0 mechanisms can be pivotal in managing supply chains more effectively during disasters or pandemics, such as COVID-19. The study by Farooq et al. (2021) examines decision-making strategies and strategic planning in industrial supply chains to evaluate how these approaches impact the survivability of manufacturing firms during disturbances. The research also examines how

COVID-19 impacts supply chain aspects such as transport and logistics, supply and demand, and resource allocation techniques. The study develops a framework that illustrates the necessity of integrating of sustainability and resilience strategies with Industry 4.0 as a foundation to effectively manage supply chain challenges during COVID-19 or other pandemics.

2.3.1 Supply Chain Management Barriers

Multiple barriers are experienced by both small and large manufacturing firms during pandemics or other forms of disaster. According to Biswas and Das (2020), SCM barriers may vary widely from one firm to another and may include aspects such as unclear organizational goals or objectives, inadequate support and commitment from the top management, mistrust and lack of collaboration between key stakeholders (especially supply chain partners and employees), poor capacity development (training and education opportunities) for the suppliers and employees, poor feedback and customer response mechanisms, poor integration between the firm and supply chain partners, and poor communication/information technology infrastructure. The barriers also vary in complexity, thereby making it critical for decision-makers to have good comprehension about them for effective mitigation measured to be implemented. Biswas and Das (2020) study the impact of COVID-19 on the escalation of supply chain barriers within the Indian manufacturing sector, a major production hub in the Asian region. The authors concluded that aspects such as inaccessibility to raw materials, lack of manpower, poor cash flow, diminished demand due to altered customer buying habits (with a focus on essential goods), impaired transportation schedules, overseas restrictions, slow credit access from financial institutions, and an overall slow movement of manufactured commodities. These impacts on the engineering manufacturing supply chain vary in severity between different firms, with the smaller and medium-sized enterprises being mostly affected because of their low capacity to invoke economies of scale and their advantages in supply chain management.

2.3.2 Engineering Manufacturing Supply Chain Risk Management

Managing SC risks is pivotal in determining how prepared a firm is in overcoming challenges caused by eventualities such as the COVID-19 pandemic. Supply chain risk management entails the variability in distribution of potential outcomes in the supply chain, their subjective values, and their likelihood, meaning that SC risks comprise flow breakdowns between various components in a supply chain (Butt, 2021). The variability has the potential to impact raw material, product, and information flows within manufacturing environments, which is detrimental to factors such as production flexibility, cost efficiency, and cycle times. SC variabilities also cause significant modifications to the use of equipment and human resources. Zsidisin, Ragatz and Melnyk (2005) define the scenario where a supply chain is at risk, as one with a high probability of failure in the inbound supply (or the supply market), often resulting in the manufacturer's inability to meet client/market demands, thereby threatening the stability of the industry. Risk can also be categorized in terms of severity or strength, or the level of probability of an incidence occurring (that is, low, medium, or high). According to Baryannis et al. (2019), supply chain risks involve different groupings, including delivery postponements, distractions, intellectual property, received materials/goods, procured items, inventory, and organizational/logistical capacity. Additionally, supply chains are susceptible to risks such as machine breakdowns, low-quality raw materials, compromised systems that impact the firm's data integrity, and stock delivery delays. Therefore, risks associated with SCM are classifiable as event exposures that result in damage or the disruption to the chain's efficient management systems (Butt, 2021). Accordingly, these aspects of risk management should be considered when evaluating the disruption of supply chains in the engineering manufacturing sector during the COVID-19 pandemic.

Supply chain risks have been researched widely over the last two decades, with a key focus on how the hazards expose SC management within a pandemic context. For instance, Dolgui et al. (2020) reported that the COVID-19 pandemic presented exclusive risks for operationally and strategically managing both local and global supply chains. The simulation model developed by Ivanov (2020a) highlights predictions regarding the possible impact of similar outbreaks on global supply chains, indicating that such impacts are slowly spreading to all continents because of the entwined nature of today's supply chains. Furthermore, pandemic occurrences could result in different risks in the interconnected and operationalized supply chains especially since greater operational risks are bolstering the competitiveness of supply chains (Butt, 2021; Dubey, Gunasekaran & Papadopoulos, 2019). Other research studies indicate that risks associated with supply chains can develop uncertainties on supply sides during epidemics or other disasters, most of which are unprecedented especially for firms lacking resilience and sustainability strategies for such times (Behzadi et al., 2018; Govindan, Fattahi & Keyvanshokooh, 2017; Williams et al., 2013). Experts indicate that COVID-19 could result in a demand-side impact on key production supply chains, either causing panic buying, creating shortages, or a supply glut for commodities that are not fast-moving or essential in nature, such as products from a manufacturing engineering firm. Currently, only a few studies have researched how organizations are extenuating the pandemic's impacts on SC disruptions. For example, the study by Sharma et al. (2020) indicated that manufacturing firms can alleviate the pandemic's impact on supply chain disruptions by adopting policies that leverage reduced inventory in the supply chain. On the other hand, Govindan, Fattahi and Keyvanshokooh (2017) posit that robust decision support systems could be the key to managing most of the imminent supply chain risks within the manufacturing sector. Dolgui et al. (2020) and Ivanov (2020a) concluded that the activation of secondary supplier relationships could be pivotal in helping manufacturers adjust and fulfil their shortages in inventory. These studies offer a wide array of information on how engineering manufacturing firms can effectively manage their broad range of supply chain risks during the COVID-19 outbreak, but there is still a gap in how likely and severely aspects such as cost efficiencies, production flexibility, and cycle times are impacted during the pandemic.

2.3.3 Additive Manufacturing Technologies and Supply Chain Risk Mitigation

The COVID-19 outbreak has highlighted major flaws in manufacturing processes today, especially regarding the management of supply chains. Recently, manufacturers have realized the potential of using automated systems to alleviate production process disruptions, including the management of supply chains. According to Kunovjanek and Wankmüller (2020), conventional production mechanisms and long-distance logistics were insufficient in fulfilling the rising demand for manufactured equipment that were urgently needed across the globe, thereby prompting the innovation of additive manufacturing (AM) techniques to cover up the deficits through computer-aided designs that can be produced in a scalable manner based on demand and at any preferable location worldwide. AM is a process that allows for the production of goods of varied complexity entirely from computer-aided designs (CADs) through the addition of layers on top of each other, which allows the producer to have a higher design freedom, more responsiveness and manufacturing flexibility, and a high level of resource efficiency (Eyers et al., 2018; Kunovjanek & Wankmüller, 2020; Zanoni et al., 2019). However, the adoption of effective manufacturing technologies, such as AM, were remarkably low since the onset of the COVID-19 pandemic, thereby highlighting a major gap in the adoption and large-scale use in different industries to ensure smooth production even with the pandemic-related restrictions. With the growing pressure to supply component parts (such as forged aluminium plates) for the production of construction, medical, and other emergency outfits, manufacturing firms had to also adhere to the strict rules regarding mitigation of the virus spread, including social distancing and ensuring the health and safety of their worker. Firms with lesser automated systems were the most adversely affected because of the mandatory reduction in the number of workers who can be at any given area of a factory. Additionally, most of the manufacturing firms were deemed non-essential services, meaning that any imminent closure of such firms had a direct impact on production. The adoption of technologies, such as AM, was thereby escalated by the pandemic situation to ensure firms remained afloat and in production. While AM is yet to be widely adopted in the engineering manufacturing sector, there has been widespread adoption of automated systems which can effectively be operated remotely through proper and robust organizational networks, systems, and applications (such as BIM and other CAD platforms).

Technological adoption can greatly improve production efficiency and reduce supply chain disruptions, thereby improving core manufacturing aspects such as production flexibility, cycle times, and cost efficiency. Moreover, with the automated systems used in Industry 4.0 mechanisms, manufacturers can improve the coordination of supply logistics based on the current barriers, grow their stockpiles according to projected demand metrics, and minimize costs through improved waste monitoring and reduced labour costs since all machines run in-situ (Kunovjanek & Wankmüller, 2020). Technologies, such as additive manufacturing, have proved effective from a multidisciplinary perspective that goes beyond engineering manufacturing. The technology allows for flexibility during disaster responses as well as for long-term recovery approaches for firms. Through automation and AM, a manufacturer can have remote teams (for example, working from home) develop CAD designs for core product parts or entire products, which can be asCFAbled at the main factory with minimal labour input, while ensuring that the production process is not adversely impacted. The adoption of such technologies also greatly increases organizational flexibility and performance since the production of parts or whole products can be up scaled or downscaled, depending on demand. Moreover, the prompt production of part or whole equipment parts via AM acts as a crucial mitigation measure for possible supply chain delays, while fostering the fast requisition of required materials. Engineering manufacturing firms can also achieve significant cuts in production costs since last-mile transfer/transportation can be minimized accordingly, while also offering the chance to scale production based on demand fluctuations as influenced by the pandemic (den Boer, Lambrechts & Krikke, 2020; Tatham, Loy & Peretti, 2015). Thus, adopting automated and virtual technologies, such as AM, could be pivotal in overcoming pandemic-related disruptions in the supply chains of engineering manufacturers by flexibly addressing the arising bottlenecks in an effective manner.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Research Paradigm

The research will employ a constructivism approach to address the research questions. Philosophy aids researchers in understanding people's perceptions of social issues (Rehman & Alharthi, 2016). The model will be used in this study because it is comprehensive and suitable for explaining the research aims and objectives, revealing participants concealed voices about the subject, and allowing the investigator to precisely interpret the research questions. Constructivism takes an epistemological approach, whereby information and knowledge are considered to be created or constructed, thereby concentrating on singular function or process analytics. According to Mittwede (2012), constructivism comprises a relativist nature, whereby realities are considered as a combination of multiple mental ideations that are intangible and founded on human experiences. Such constructs are not assessed based on how true they are, but on their level of sophistication or informativeness. Based on critical theory, constructivism bears an epistemology that is transactional in nature, while the findings of related studies are ideally developed depending on how the investigation progress. Moreover, the methodological approach embodied in constructivism is based on dialectical interchanges, with the goal of precipitating better informed/sophisticated constructions. Therefore, the ultimate goal of a constructivist approach is to reconstruct or develop informative knowledge areas on a subject, which can later be revised continuously based on new evidence. On the other hand, Honebein (1996) construes constructivism as a research/philosophical model whereby the investigator can develop their personal knowledge and understanding of the world via intricate experiences that guide their reflections and interpretations more analytically and objectively in a way that can influence policy decisions significantly. The approach is founded on the interpretation that people develop most of what they know or learn through detailed experiences, which creates the general meaning that constructivism is equitable to learning (Adom, Yeboah & Ankrah, 2016). Thus, the constructivist research paradigm is an effective tool with multiple advantages when used in studying variables in diverse disciplines, thereby informing crucial managerial or organizational decisions.

Embodying an inclusive research paradigm is crucial for any study. The constructivist approach guides the investigator in developing their own knowledge and comprehension of the study metrics by evaluating the correlations between the variables and how they are related to current literature and research findings. To further understand how the primary study variables (i.e. production flexibility, cycle times, and cost efficiency) were influenced by the COVID-19 pandemic disruptions, the study needed to construct these interrelations from current studies using similar models. According to Alkahtani et al. (2021), past studies focused on the analysis of diverse models in supply chains in calamity-based situations. From a constructivist point of view, these approaches enlightened the previous approaches embodied by firms to mitigate their supply chain disasters, while also indicating that inter-organizational coordination and key production policies were crucial in determining the outcome of such disaster management initiatives. Such studies also had to consider the impact of socioeconomic and political issues, such as the lack of accountability, poor transparency, and corruption, when determining whether supply chain disaster management during disasters would be effective. Therefore, any robust and valuable supply chain should lay emphasis on assessing the core needs of an organization before engaging any mitigation efforts. Alkahtani et al. (2021) posit that supply chain robustness is founded on the chain's flexibility especially since production processes during disasters, such as COVID-19, significantly differ from normal times. Therefore, emergency supply chain management should incorporate role definition, model establishment, and overall chain coordination efforts, particularly tailored for special occasions, such as the recent pandemic.

Thus, this constructivist approach augments why production flexibility should be included in this study as a variable.

Flexibility in production systems also influences other variables, which in this case include cycle times and cost efficiencies during the pandemic period. Flexibility in cycle/lead times (including production rates, times, and processes) significantly improves the resilience of organizational supply chains. Such flexibilities also improve the cost-reduction goals in a firm especially during calamity periods. Alkahtani et al. (2021) states that the reduction of cycle times could further be impacted by the COVID-19 pandemic, which presents an external environmental factor that is ideally uncontrollable, thereby influencing demand uncertainties. In such cases, controlling the production rates is an effective strategy. With global supply chains, most modern-day firms rely on inputs from abroad markets. Any derailment in the supply of such commodities, for example, the recent interruption by the coronavirus pandemic, results in major production and market/distribution anomalies. However, companies with robust supply chain management models which can maintain control and flexibility of their manufacturing processes are able to have optimized cycle times that match the demands of a fluctuating market environment. The economic production lot size model (EPL model) by Larsen (2005) (whereby more than one rates of production can be adopted during a cycle) illustrates flexible production cycles with dynamic runs that result in varied rates of production befitting the changing market demand. The study further indicates that the rate of production at a firm should consider the value lying between the production and demand rates as a platform for determine proper management of production costs (i.e., cost efficiency).

The constructivist nature of this study also considers how the various parameters or variables being researched (that is, flexibility, cycle times, and cost efficiency) are correlated, including how each parameter impacts the other during the pandemic period. The production environment in the course of any calamity faces multiple challenges that impact production and its effectiveness, including factors such as demand uncertainty and production defects, and how such aspects impact manufacturing costs. In today's advanced work environment, adopting Industry 4.0 alongside lean manufacturing practices could result in significant cost savings in a resource-strained (i.e., both human resources and raw materials/inputs) production environment. Connolly and Sheahan (2002) present a computerized manufacturing setup/model, whereby the supply chain framework is conjoined with the manufacturing processes/systems as a way to minimize the setup costs amidst a catastrophe and lower the number of defective products produced, thereby augmenting the cost efficiency of an entire manufacturing organization. With the COVID-19 pandemic presenting unexpected situations in the distribution of inputs and finished products, thereby considerably impacting supply chain management from a social and economic perspective, it is crucial for investigators to adopt research philosophies that address these current issues for firms to develop resilience measures for their respective supply chains. Accordingly, this study adopts the constructivist research paradigm to develop epistemological ideations on how the research variables are impacted by the COVID-19 pandemic disruptions, and how such variables influence or correlate with each other in an organization's supply chain.

3.2 Research Techniques

The constructivist research paradigm is particularly linked with quantitative methods of research because the model seeks to develop an understanding on the study aspects from the investigator experiences and the angles used by the participants to develop the required data using different mediums. Additionally, the researcher can develop an understanding of the study variables or factors via their personal experiences in relation to those of the research participants. Therefore, through this paradigm, the investigator can evaluate the information collected from her subjects based on established facts. The researcher may also engage in the data collection activities within the organization being studied to establish a better bond with the truth of the information she is gathering. However, this approach was not possible because of the current social distancing restrictions under the COVID-19 rules. It is important to note that the constructivist approach in quantitative research considers the reality of any data/information collected from the participants to be subjective since it includes varied or multiple individual perspectives that are influenced by a broad array of factors (Adom, Yeboah & Ankrah, 2016). Thus, the current research will include a close-ended inquiry through a structured questionnaire, whereby valid/tentative conclusions are developed from the study findings to inform organizational policy decisions.

The research method use in this study in line with the constructivist approach is a case study. Adom, Yeboah and Ankrah (2016), stipulate that case studies, like other research methods under the constructivist approach (such as ethnographic, descriptive, and narrative studies), require a significant amount of time to develop an understanding of the aspects being studied, whereby the investigators are mostly required to spend time with their test subjects to contextualize the factuality of the data being collected. In the current study, this challenge was overcome by first assessing the best suited candidates to include as participants in the study, with one of the most important qualifying aspects being "those who have worked in the firm for three years and above." The approach eliminated the need to ascertain that all participants could comprehend and respond factually to the various key factors/questions related to the study variables. Figure 1 above includes a theoretical framework which is a key aspect in constructivist studies, whereby the investigator can inductively create or generate a theoretical model or pattern that construes a specific meaning relating to the study, with the current model indicating the possible correlations between the study variables (cycle times, production flexibility, and cost efficiency) and the key disrupting factors in the supply chain.

Based on these intuitions, this study will deploy a quantitative research approach, using a standard questionnaire disseminated electronically to respondents. As a result, this design will allow the researcher to examine a broader range of answers while still driving valuable meaning (Saunders, Lewis & Thornhill, 2009). This survey will be created using structured questionnaires derived from previous literature and distributed electronically through mail or direct survey link to respondents. A well-designed quantitative study is generally productive and systematic, requiring the investigator to statistically record experiences and observations while collecting data. Particularly, the quantitative design is the most appropriate method since it can accommodate a larger sample size, and since it may be difficult to meet managers and CEOs during certain COVID period, so, a quantitative technique allows surveys to be sent digitally and responses to be collected and analysed statistically.

3.3 Research Data Collection

To answer the research questions, this study will rely on both primary and secondary data. According to Fusch and Ness (2015), using many data sources can help gain a more comprehensive understanding of the subject. The researcher will collect primary data through the use of structured questionnaires based on previous literature, whereby respondents will reply to close-ended questions (i.e., a rating scale on the likelihood and severity of the various variables under study). Structured questionnaires are suitable because they permit the researcher to collect responses from a wider audience, it is the best to use at this time, because the COVID-19 restriction would limit any one-on-one meeting session on the research subject. Secondary data will be collected from a variety of peer-reviewed academic publications, journal articles, books, and articles found on credible websites. The researcher will assess the accuracy, suitability, and relevance of the secondary sources in a methodical manner. The researcher will eventually be able to adequately answer the research questions using primary and secondary data.

Quantitative data was collected for the study. The study utilized a constructivist instrumentation approach that entails observation, collecting data, review of documents/literature, and visual analysis of data (Adom, Yeboah & Ankrah, 2016). However, the investigator is assured of flexibility when collecting the data, hence the use of structured questionnaires. In this study, the researcher used a quantitative structured questionnaire to gather the information from the participants, whereby they were required to tick boxes with the most appropriate answers. Categories for the questionnaire included demographic information (i.e., age group, gender, length of time working with the organization/industry, and educational status/level). The questionnaire was further divided into three primary sections (for each of the primary variables – cycle times, production flexibility, and cost efficiency), with each participant determining the likelihood and severity of each variable being affected by various supply chain disruption aspects on a scale of Likert 1-5. The supply chain disruptions under scrutiny included drops and surges in demand fluctuations, storage and access restrictions, human resource shortages, component/raw material shortages, alternative suppliers, supply chain automation, Communication within the supply chain, and stakeholder/third-party involvement. The questionnaire included a list of questions posed to consenting participants of the research. The questions posed were structured to explore how the management in engineering manufacturing firms make evidence-based decisions when tackling or mitigating supply chain disruptions during pandemics, and to recommend ways of improving or managing process effectiveness (cycle times, production flexibility, and cost efficiency) during disasters/pandemics with the consideration of various factors such as Communication throughout the supply chain and mitigating raw material shortages.

3.4 Research Population and Sampling

The researcher will use a sufficient sample size to reach valid inferences. A quantitative design designates the deployment of a broader sample size, with sufficient data on the research subject easily collected electronically. In order to meet the research aims and objectives, the study participants included professionals from an engineering manufacturing sector, for example, engineers, supply chain and logistics staff, the management, or any employee with substantial experience within the facility. To participate in the study, a potential respondent must have worked in their industry/facility at least three years before the pandemic to have acquired adequate understanding of how coronavirus has impacted its operations. The most experienced and knowledgeable individuals were encouraged to participate in the study to generate usable data. The study participants were also selected based on their willingness, readiness, and reachability, while insightfully sharing the required information for the research. However, participation in the study is completely voluntary and each of the participants had the freedom to excuse themselves at any point. The researcher also addressed any arising issues during the study process as promptly as possible. A purposive sampling strategy will help the researcher select the study's respondents. Purposive sampling entails identifying and choosing knowledgeable and experienced individuals to participate in the study (Palinkas et al., 2015). The investigator employed a purposive sampling method to identify and select 700 engineering professionals in the related organization. At the end of the data collection process, 500 usable questionnaires were gathered, coded (using the study's Codebook for Data Entry), and entered in Excel for cleaning and analysis. Overall, this purposive sampling strategy was suitable for the study because it portrayed resource effectiveness while facilitating the selection of the most experienced and knowledgeable individuals to participate in the study.

3.5 Research Analysis Tools

Data analysis is usually conducted using inductive approaches from the data collected in a research study. Arising conclusions are developed from such data, with the application of logical data analysis and reasoning (Mittwede, 2012). Based on the research design, objectives, and questions, the investigator begins her analysis through a slow but rigorous approach, from generalizations to specifics. Adom, Yeboah and Ankrah (2016) alerts investigators that by embodying a constructivist model of analysing their data, they should develop a picture of the ideas taking shape throughout the collection and examination of the data. Thus, the researcher must consider what influences they have as an individual so as to manage minimize biases and other subjective aspects such as emotions when drawing conclusions and developing meanings of the information they have. Accordingly, this study will embrace intuitive insights from current literature to evaluate analytical outcomes regarding how supply chain disruptions impact cycle times, production flexibility, and cost efficiency. Objectivity will be maintained with the use of renowned software (SPSS) in order to draw valid insights and conclusions that can inform pivotal policy changes in affected organizations within the engineering manufacturing sector.

The researcher will leverage a quantitative analysis to examine the collected data using statistical tools, particularly SPSS. This data evaluation method will entail pinpointing emerging observations, trends, and themes from the collected data. It will also permit the researcher to identify common themes by thoroughly designating the participants' experiences. Afterward, the investigator will compare the respondents' views and reach informed conclusions concerning the research subject. Quantitative analytical method will be suitable because the data gathered will be done using Microsoft Forms and Excel, mostly because of the current safety concerns caused by COVID-19 and the unavailability of the respondents for one-on-one interview sessions.

3.6 Research Ethical Considerations

The investigator focused on conducting an ethical study. Though the study embodies a quantitative research design, there was relatively little interaction between the participants and the researcher, since the data was collected through questionnaires provided electronically to the respondents. Moreover, this research was generally rolled out as an enterprise embodying trust and mutual respect between the investigator, the participants, and other stakeholders (including public and academic audiences). Therefore, the study was subjected to ethical review to ensure that it was carried out in conformance with its responsibilities to each participant and the wider public. The ethical review of this study was specifically aimed at ensuring that any foreseeable harm to the psychological, social, and physical well-being, values, health, and the dignity of all participants, the investigator, and other affiliated stakeholders was minimised; and that their rights are upheld (including the participants' right to confidentiality, anonymity, privacy, and informed consent). Additionally, this questionnaire was distributed electronically and in accordance to the current COVID-19 restrictions and regulations.

CHAPTER FOUR: RESEARCH RESULTS ANALYSIS AND DISCUSSION

The analysis and results/findings section will include the various analytical methods used on the gathered data after performing cleaning and reliability tests. The primary analyses performed include exploratory factor analysis (EFA) (integrating the KMO and Cronbach Alpha tests) and correlations. The IBM SPSS v.23 (SPSS - Statistical Package for the Social Sciences) was used for the analyses, i.e., the descriptives, EFA, and correlations. Data reliability was conducted on SPSS using the Cronbach Alpha test, whereby alpha values greater than 0.7 are indicative of reliable data. Separate reliability tests were run on the three primary variables (i.e., cycle times, production flexibility, and cost efficiency), generating alpha values of 0.700, 0.763, and 0.745, respectively. Therefore, the data used for various analyses was reliable.

4.1 Descriptive Statistics

Tables 1, 2, 3, and 4, alongside Figures 2, 3, 4, and *5* below highlight the descriptive statistics for the study. The figures illustrate the normal distribution of the descriptive data for the study. According to the frequencies, most of the participants were male (97.4% - Table 1/Figure 2). In terms of age groups, most of the participants (43%) were aged between 24 and 40 years (Table 2/Figure 3). A slightly higher percentage of the respondents (36%) had worked at the plant or organization for five to seven years (Table 3/Figure 4) and 46.6% had at least a college degree (with 1.8%, 43.2%, and 8.4% having attained high school, Bachelor's, or Master's education, respectively) (Table 4/Figure 5).

Table 1 Gender Distribution Among the Study Participants

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Male	487	97.4	97.4	97.4
	Female	13	2.6	2.6	100.0
	Total	500	100.0	100.0	

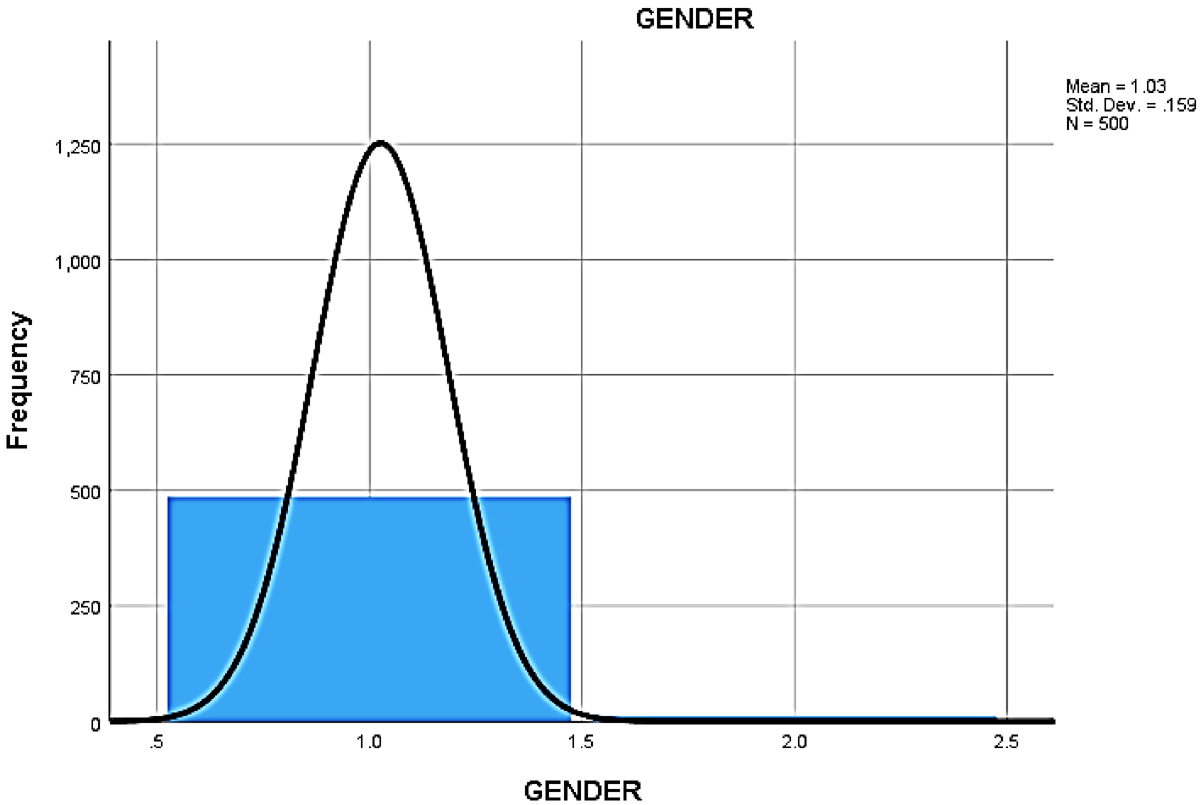

Figure 2 Normal Distribution for Gender Distribution Among the Study Participants

Table 2 Age Group Frequencies Among the Study Participants

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	18-24 years	118	23.6	23.6	23.6
	24-40 years	215	43.0	43.0	66.6
	40-60 years	130	26.0	26.0	92.6
	Over 60 years	37	7.4	7.4	100.0
	Total	500	100.0	100.0	

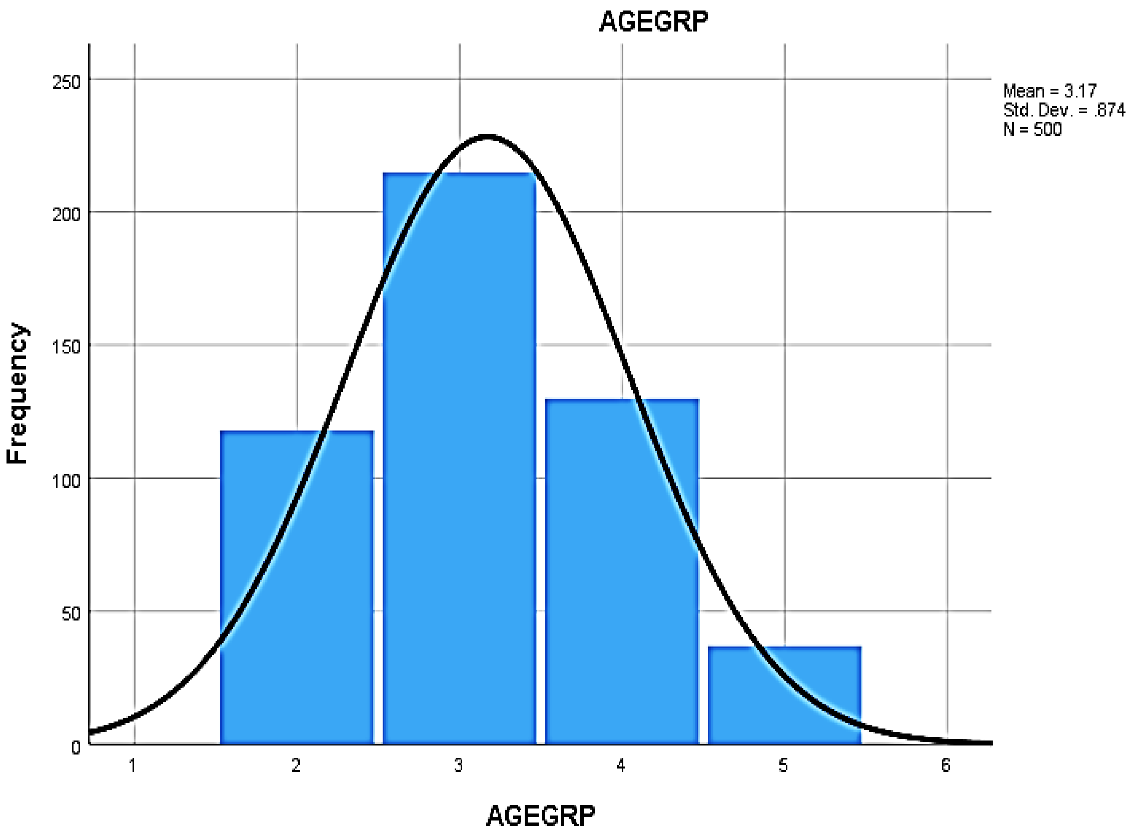

Figure 3 Normal Distribution for Age Group Frequencies Among the Study Participants

Table 3 Length of Time Working at the Plant/Organization

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	3-5 years	139	27.8	27.8	27.8
	5-7 years	180	36.0	36.0	63.8
	7-10 years	110	22.0	22.0	85.8
	Over 10 years	71	14.2	14.2	100.0
	Total	500	100.0	100.0	

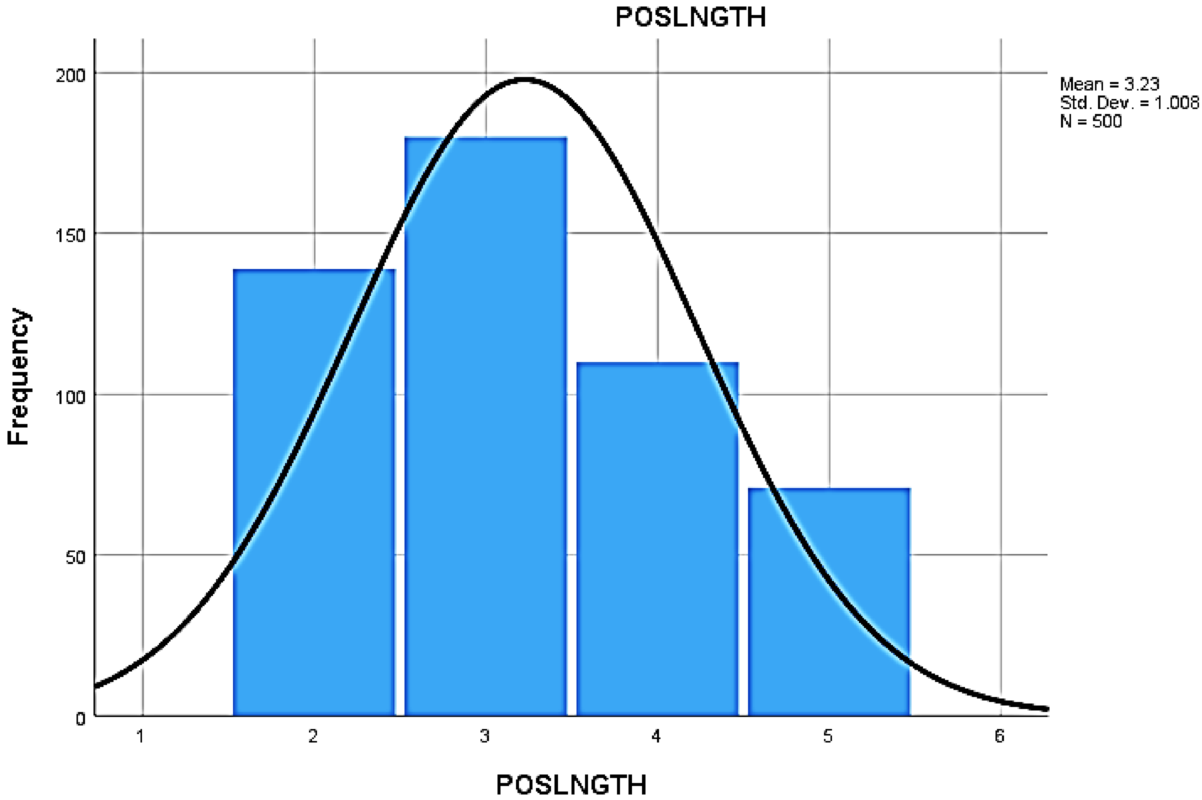

Figure 4 Normal Distribution for Length of Time Working at the Plant/Organization

Table 4 Education Status/Level

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	High school	9	1.8	1.8	1.8
	College degree	233	46.6	46.6	48.4
	Bachelor’s degree	216	43.2	43.2	91.6
	Master’s degree	42	8.4	8.4	100.0
	Total	500	100.0	100.0	

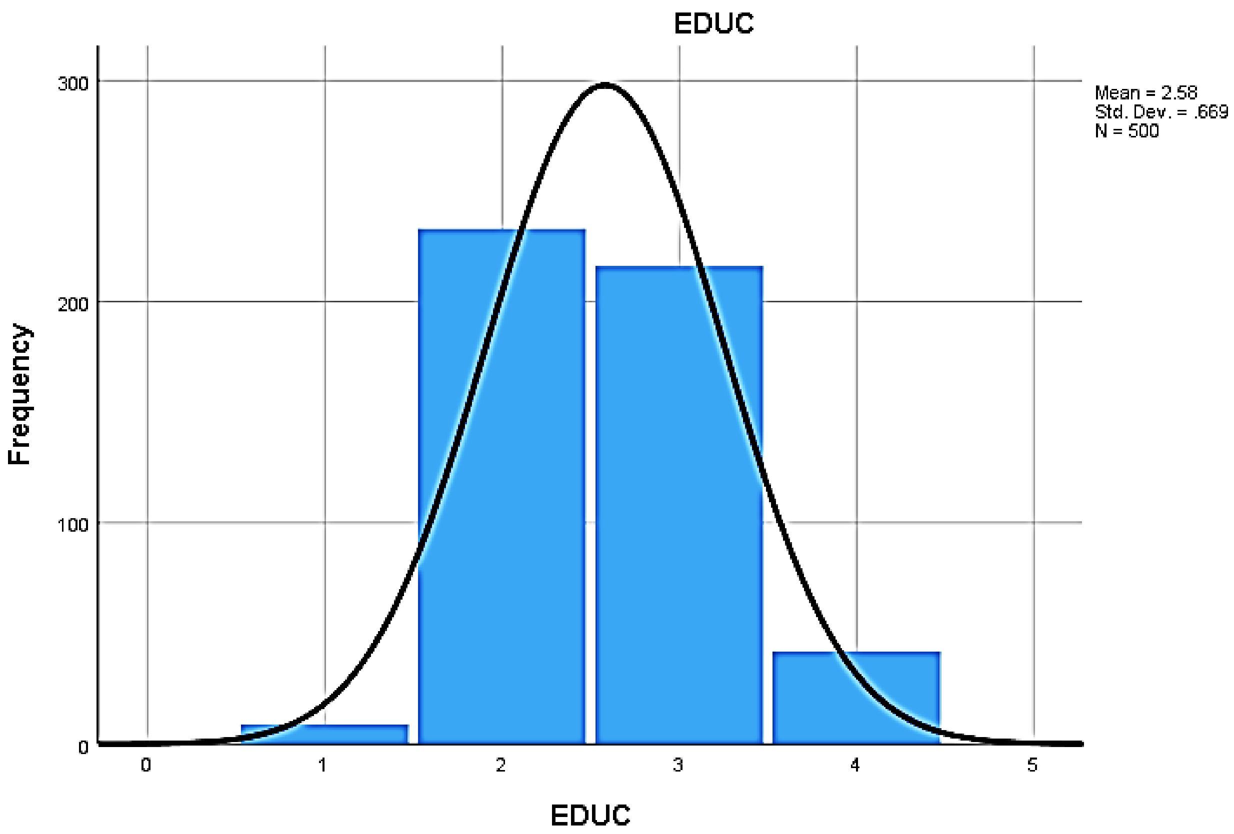

Figure 5 Normal Distribution for Education Status/Level

Table 5 Mean, Median, and Mode

		AGEGRP	GENDER	POSLNGTH	EDUC
N	Valid	500	500	500	500
	Missing	0	0	0	0
Mean		3.17	1.03	3.23	2.58
Median		3.00	1.00	3.00	3.00
Mode		3	1	3	2

Measures of Central tendency were used for the descriptives in the dataset as included in Table 5 above. The mean includes the arithmetic average of a distribution or a dataset/set of numbers obtained by adding up all values and dividing the total by the number of values, which in this case is 500 iterations (i.e., N=500). The mean age group was 3.17 which translates to 24-40 years, i.e., most of the study participants were between 24 and 40 years. The mean for the gender was 1.03, i.e., most respondents (97.4%) were men. The mean position length was 3.23, meaning that a significant percentage of the participants had worked at the firm for five to seven years. Education level averaged at 2.58, meaning that most respondents were college educated.

The median signifies the value that occurs right at the middle of the dataset when the values/entries are arranged from low to high. The median is the numeric value separating the lower half of a probability distribution, population, or sample from the higher half. For the study's dataset, the median age group was 3.00, that is, 24-40 years. The median gender was 1.00, i.e., male. The median length of time working at the firm was 3.00, i.e., 5-7 years, and the median education status/level was 3.00, i.e., Bachelor's degree.

Mode indicates the most commonly occurring value in a sample or dataset, meaning that most of the participants were represented by this value. For the age group, the mode was 3 (24-40 years); Gender was 1 (male), length of time working at the firm was 3 (5-7 years); and education status/level was 2 (college degree).

4.2 Exploratory Factor Analysis: Results and Discussion

Factor analysis is a widely applied multivariate statistical approach in engineering research. The analytical method, as a data reduction technique, is employed in the identification of underlying variable structures through the examination of variable interrelationships, while also categorizing them into smaller factor clusters or latent factors. Two primary analytical mechanisms emerge from factor analysis: confirmatory factor analysis (CFA) and exploratory factor analysis (EFA). CFA entails an attempt to test hypothesized factor model significance levels via an examination of whether the proposed model(s) conform to the analysed data. On the other hand, EFA does not have a definitive number of anticipated factors for the data being explored. However, the investigator explores to develop a best fit model for a specific data set (Aryadoust & Raquel, 2019). EFA evaluates the correlational patterns among the variables being observed (such as survey questions or test items) to generate the lowest number of factors that are common in the data set based on their interrelationships, while also achieving the least number of assumptions in both the analyses and results. Instead of conducting analyses on each variable separately, EFA makes summaries of the relationships and patterns among the sub-variables and clusters them into several factors (whereby each consists of at least three variables/sub-variables). Therefore, EFA is employed to recognize the underlying factors that can best interpret the data.

Factors entail the fundamental dimensions which give an interpretation of the observed variance among the study variables. Thus, factors can define the interrelations between the observed variables. According to Aryadoust and Raquel (2019), large correlational coefficient clusters between study variables/sub-variables are indicative of the variables evaluating similar underlying dimensions. Upon developing specific factors or item clusters, the investigator can effectively interpret or label them through a thorough assessment of the substantive meaning and content of the questions that are grouped together in each cluster/latent factor. EFA constitutes five pivotal steps: assessing if the data is appropriate for carrying out EFA, choosing a suitable factor extraction approach for factor derivation, deciding on the ideal number of factors for retention, selecting an approach for rotating the factors for optimized factor solution, and interpreting the generated factor solutions/clusters.

4.2.1 Exploratory Factor Analysis Results/Analysis

The following tables (Tables 6-8 below) illustrate the EFA results/analysis for this study. The tables indicate the rotated component matrices for the three primary variables (cycle times, production flexibility, and cost efficiency, respectively) using PCA and the Varimax rotation method. Accordingly, three latent factors were obtained for the cycle times variable (see Table 6), three factors for the production flexibility variable (see Table 7), and three factors for the cost efficiency variable (see Table 8). These factors were used as the theoretical basis for conducting correlations for the study.

*Table 6 The Rotated Component Matrix of the Cycle Times Variable Using PCA and the Varimax Rotation Method (*n *= 500)*

	Component		
	1	2	3
[CYCLETIME7LIK] How Likely are Cycle Times Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	.911		
[CYCLETIME8SEV] How Severely Are Cycle Times Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	.908		
[CYCLETIME5LIK] How Likely are Cycle Times Affected by Labor Shortages?		.905	
[CYCLETIME6SEV] How Severely are Cycle Times Affected by Labor Shortages?		.902	
[CYCLETIME4SEV] How Severely are Cycle Times Affected by Storage and Access Restrictions?			.999
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.			
a. Rotation converged in 3 iterations.			

*Table 7 The Rotated Component Matrix of the Production Flexibility Variable Using PCA and the Varimax Rotation Method (*n *= 500)*

	Component		
	1	2	3
[PRODUCTIONFLEX7LIK] How Likely is Production Flexibility Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	.960		
[PRODUCTIONFLEX8SEV] How Severely is Production Flexibility Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	.944		
[PRODUCTIONFLEX5LIK] How Likely is Production Flexibility Affected by Labor Shortages?		.957	
[PRODUCTIONFLEX6SEV] How Severely is Production Flexibility Affected by Labor Shortages?		.945	
[PRODUCTIONFLEX13LIK] How Likely is Production Flexibility Affected by Communication Throughout the Supply Chain?			.897
[PRODUCTIONFLEX14SEV] How Severely is Production Flexibility Affected by Communication Throughout the Supply Chain?			.889

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 4 iterations.

Table 8 The Rotated Component Matrix of the Cost Efficiency Variable Using PCA and the Varimax Rotation Method (n = 500)

Rotated Component Matrix[a]			
	Component		
	1	2	3
[COSTEFFICIENCY9LIK] How Likely is Cost Efficiency Affected by Alternative Suppliers?	.963		
[COSTEFFICIENCY10SEV] How Severely is Cost Efficiency Affected by Alternative Suppliers?	.944		
[COSTEFFICIENCY15LIK] How Likely is Cost Efficiency Affected by Third Party/Stakeholder Involvement?		.897	
[COSTEFFICIENCY16SEV] How Severely is Cost Efficiency Affected by Third Party/Stakeholder Involvement?		.888	
[COSTEFFICIENCY7LIK] How Likely is Cost Efficiency Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?			.901
[COSTEFFICIENCY8SEV] How Severely is Cost Efficiency Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?			.880
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.			
a. Rotation converged in 4 iterations.			

4.2.2 Discussion of Exploratory Factor Analysis Results

4.2.2.1 Step 1: Assessing the Dataset

The initial EFA step involves checking whether data is suitable and sufficient for analysis. EFA has a crucial assumption regarding the linearity of variable relationships, which means that two variable sets are representable with a line. Violating this assumption could generate bogus or non-content-based latent factors (Aryadoust & Raquel, 2019). In addition to establishing linearity, substantial correlations have to be demonstrated. According to Hair et al. (2010), EFA would be unsuitable if there are few or no interrelation coefficient exceeding .30. Large data samples are crucial when conducting EFA, although perspectives between different researchers on the most appropriate sample size vary significantly. For instance, Comrey and Lee (1992) argue that a sample size of 500 is very good, while that of 300 is good. Conversely, Fidel (2013) stipulates that 300 participants are sufficient, while Hair et al. (2010) posit that 100 cases or more are enough to conduct EFA. Subject-to-variable (STV) ratios are also important when conducting factor analysis, with a range of 2:1 to 20:1 or higher being suitable. Hair et al. (2010) recommend a 20:1 ratio, with other studies endorsing ratios ranging from 2:1 to 10:1. The STV ratio for the dataset was sufficient for EFA analysis. The current study utilized a Cronbach Alpha test with dimension reduction and the KMO and Bartlett's test of sphericity to check the dataset for suitability in factor analysis, whereby an Alpha value of 0.7 or more is considered appropriate. With an overall Cronbach Alpha score of 0.748 for all primary variables and individual scores of 0.700, 0.763, and 0.745 for the cycle times, production flexibility, and cost efficiency, respectively, the data used in this study shows a high level of consistency and reliability (showing how closely related the sub-variables are as a group). Ideally, a higher Cronbach Alpha score indicates a higher level of inter-variable correlation. Hence, the sub-variables in the production flexibility data set had the highest inter-item correlation in the study's dataset. Overall, the Cronbach Alpha values (with KMO and Bartlett's testing to determine sample adequacy) showed that the dataset is suitable for EFA analysis.

4.2.2.2 Step 2: Extracting the Latent Factors

The main objective of factor extraction from the correlational matrix is to come up with an appropriate decision regarding the number of latent factors. Different levels of variance for the study variables/sub-variables are defined by the extracted factors. For instance, the factor that is extracted first in the EFA analysis is indicative of the highest variability level among the sub-variables, with the second, third, fourth, and/or fifth following a similar pattern of variability (that is, the first factor has the highest variability level while the last has the lowest variability amongst the observed variables). Aryadoust and Raquel (2019) highlight various factor extraction techniques used by researchers, including maximum likelihood, principal axis factoring (PAF), and principal component analysis (PCA). The latter, PCA, is the most widely used in EFA. The current study also adopted PCA for its factor extraction process. IBM SPSS 23 was used to perform a principal component analysis for extracting eigenvalues for the study data. The PCA method was preferred for its ability to maximize data interpretation.

4.2.2.3 Step 3: Establishing the Number of Factors

Various approaches are used when establishing the most suitable number of extracted latent factors, whereby two mechanisms are common; the use of scree plots or assessing the total value/magnitude of the eigenvalue. The latter method was adopted in this study because of its ability to maximize data interpretation while using PCA. Known as the Kaiser (1960) approach, this technique of factor determination utilizes the eigenvalues to mirror the defined variance by each factor, indicative of each factor's importance. Based on the PCA outcomes in the EFA analysis, a five-factor solution was found to be suitable for this study since it maximized data interpretability for the cycle times variable; six factors for the production flexibility variable; and five factors for the cost efficiency variable. Thus, the respective factors featured in each of the variables' rotation matrices were used to build the respective CFA models for each primary variable.

4.2.2.4 Step 4: Factor Rotation

After extracting the various latent factors for each primary variable, they are rotated to develop a more straightforward interpretation and simplification of the categorizations. Failure to rotate these factors would result in higher loadings for most sub-variables correlated to the most crucial factor (i.e., factor 1), and smaller loadings on the rest of the factors, creating difficulties in factor solution interpretation. Therefore, conducting rotations reassesses the factors to ensure the sub-variables can load maximally onto the factors which they are most suited. Aryadoust and Raquel (2019) posit that the selection of a rotation technic should be based on producing the optimal interpretation and best fit for the study data both conceptually and statistically. Commonly applied rotation methods include oblique and orthogonal rotation. Oblique factor rotation methods (including Promax and Direct Oblimin) tend to create assumptions that the factors have interrelations, whereby Promax is suitable for significantly larger datasets while Direct Oblimin may have limitations on allowing correlations between factors when set to certain values, hence not quite suitable for this study. On the other hand, Orthogonal factor rotation methods (such as Equamax, Quartimax, and Varimax), have the general assumption of lack of correlation between factors. Varimax, which was employed in this study, is suitable since it can load smaller variable/sub-variable numbers onto each factor, thereby developing a clearer and applicable factor structure (Aryadoust & Raquel, 2019; Hair et al., 2010). With internal consistency and reliability scores (Cronbach Alpha values) of the data being acceptable for each primary variable (i.e., 0.700, 0.763, and 0.745 for the cycle times, production flexibility, and cost efficiency, respectively), rotation of the factors was suitable, generating five, six, and five factors, respectively, for each of these variables after EFA analysis. As shown in Tables 6, 7, and 8 the range of the factor loadings was 0.902-0.999 for the cycle times variable, 0.889-0.960 for the production flexibility variable, and 0.880-0.963 for the cost efficiency variable; all these loadings were significantly greater than the recommended level (0.30) for optimal factor allocation.

4.2.2.5 Step 5: Factor Interpretation

Obtaining the factor solutions prompts the interpretation of the generated factors, which includes the examination of all factor loadings for each primary variable and determining the correlation between the sub-variables and factors, while also suitably labelling each of these factors. As indicated earlier, several questions, or sub-variables, load onto each factor. Higher loading values are indicative of advanced correlations between a sub-variable and a specific factor, thereby making such a sub-variable more illustrative of that factor. Research studies stipulate that loading values exceeding 0.30 are suitable for factor loading, while three or more variables should be loaded to each factor for substantive interpretation (Aryadoust & Raquel, 2019; Hair et al., 2010). In this study, all of the sub-variables (representing the three primary variables) had high load values, with the least being 0.880 (in the cost efficiency variable) and the highest being 0.999 (in the cycle times variable). Additionally, an examination of the substantive and content meanings of the sub-variables affiliated to each factor (particularly those with higher load values), the investigator can develop with suitable factor labels that accurately reflect each construct (Aryadoust & Raquel, 2019). Based on the EFA findings, this study developed several factor labels for each of the primary variable factor loadings. For the cycle times variable, the five factors were designated as Cycle of Supply Chain (Cycle times in SC) Raw Material/Component Shortages; Labour Shortages; and Access Restrictions. For the production flexibility variable, the six factors were designated as Production Flexibility in the Supply Chain (Production Flexibility in SC) Raw Material/Component Shortages; Labour Shortages; and Communication. Finally, for the cost efficiency variable, the six factors were labelled as Cost Efficiency in the Supply Chain (Cost Efficiency in SC) Alternative Suppliers; Third-Party Involvement; and Raw Material/Component Shortages.

4.2.2.6 Measurement of Variables

Based on the summated scales, the summated variables were measured using a set of questions for each primary variable, i.e., Cycle Times, Production Flexibility, and Cost Efficiency. For the Cycle Times variable, there were three questions measuring the summated variables, including CYCLETIME4SEV: How severely are cycle times affected by storage and access restrictions? CYCLETIME5LIK6SEV: How likely and severely are cycle times affected by labor shortages? CYCLETIME7LIK8SEV: How likely and severely are cycle times affected by raw material/ component shortages (critical materials/ components)? The measurement of these variables was based on current literature which discusses the impacts of the COVID-19 pandemic on storage access (or access to stored raw materials for firms), the pandemic's impact on labor shortages as well as raw material shortages, including a review on how these impacts disrupted cycle times for manufacturers (Ambrogio et al., 2022; Butt, 2021; Kapoor et al., 2021; Zhu et al., 2020).

For the Production Flexibility variable, there were also three questions measuring the summated variables, including PRODUCTIONFLEX5LIK6SEV: How likely and severely is production flexibility affected by labor shortages? PRODUCTIONFLEX7LIK8SEV: How likely and severely is production flexibility affected by raw material/ component shortages (critical materials/ components)? PRODUCTIONFLEX13LIK14SEV: How likely and severely is production flexibility affected by communication throughout the supply chain? Current literature extensively discusses how production flexibility was affected by factors such as labor and raw material shortages, and communication ineffectiveness during the pandemic period within the manufacturing industry (Okorie et al., 2020; Siagian et al., 2021; Yawson, 2020; Zimmerling & Chen, 2021). Thus, these questions were derived from the current literature on the effects of labor/raw material shortages and communication issues on production flexibility.

For the Cost Efficiency variable, three questions were used to develop the summated variables, including COSTEFFICIENCY7LIK8SEV: How likely and severely is cost efficiency affected by raw material/ component shortages (critical materials/ components)? COSTEFFICIENCY9LIK10SEV: How likely and severely is cost efficiency affected by alternative suppliers? COSTEFFICIENCY15LIK16SEV: How likely and severely is cost efficiency affected by third party/stakeholder involvement? The studied literature discusses the impact of raw material shortages, the involvement of third parties or stakeholders, and working with alternative suppliers on cost efficiency outcomes especially for manufacturing firms (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020). While other aspects, such as the flexibility of production lines, also affect cost efficiencies in manufacturing, the selected questions used to measure the variables highlight the most common factors that impact cost efficiency.

4.2.3 Correlation Analysis and Discussion

The following tables (Tables 9-14) below illustrate the correlation results/analysis for this study. Pearson correlations were conducted between the three primary dependent variables (Cycle Times, Production Flexibility, and Cost Efficiency) and the independent variables (Raw Material Shortages and Communication). The correlations were based on the rotated component matrices for the three primary variables (Cycle Times, Production Flexibility, and Cost Efficiency, respectively) using PCA and the Varimax rotation method.

Table 9 Correlation Between Cycle Times Variables and Raw Material Shortages

		[RAW MATERIAL SHORTAGES] During the Pandemic, the Shortages of Raw Material in the Supply Chain Have Resulted in Cost Increase.
[CYCLETIME4SEV] How Severely are Cycle Times Affected by Storage and Access Restrictions?	Pearson Correlation	-.019
	Sig. (2-tailed)	.680
	N	500
[CYCLETIME5LIK6SEV] How Likely and Severely are Cycle Times Affected by Labor Shortages?	Pearson Correlation	-.016
	Sig. (2-tailed)	.714
	N	500
[CYCLETIME7LIK8SEV] How Likely and Severely are Cycle Times Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	Pearson Correlation	.031
	Sig. (2-tailed)	.496
	N	500
	Sig. (2-tailed)	
	N	500

Table 10 Correlation Between Cycle Times Variables and Communication/Knowledge Transfer

Correlations

		[COMMUNICATION] During the Pandemic, the Firm Faced Challenges in Process Cycle Times as a Result of Poor Communication Throughout the Supply Chain.
[CYCLETIME4SEV] How Severely are Cycle Times Affected by Storage and Access Restrictions?	Pearson Correlation	.049
	Sig. (2-tailed)	.271
	N	500
[CYCLETIME5LIK6SEV] How Likely and Severely are Cycle Times Affected by Labor Shortages?	Pearson Correlation	.023
	Sig. (2-tailed)	.611
	N	500
[CYCLETIME7LIK8SEV] How Likely and Severely are Cycle Times Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	Pearson Correlation	-.010
	Sig. (2-tailed)	.815
	N	500

Table 11 Correlation Between Production Flexibility Variables and Raw Material Shortages

Correlations

		[PRODUCTIONFLEX5LIK6SEV] How Likely and Severely is Production Flexibility Affected by Labor Shortages?	**[PRODUCTIONFLEX7LIK8SEV]** How Likely and Severely is Production Flexibility Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	**[PRODUCTIONFLEX13LIK14SEV]** How Likely and Severely is Production Flexibility Affected by Communication Throughout the Supply Chain?]	**[RAW MATERIAL SHORTAGES]** During the Pandemic, the Shortages of Raw Material in the Supply Chain Have Resulted in Cost Increase.
[PRODUCTIONFLEX5LIK6SEV] How Likely and Severely is Production Flexibility Affected by Labor Shortages?	Pearson Correlation	1	.288**	.251**	-.001
	Sig. (2-tailed)		.000	.000	.982
	N	500	500	500	500
[PRODUCTIONFLEX7LIK8SEV] How Likely and Severely is Production Flexibility Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	Pearson Correlation	.288**	1	.254**	-.011
	Sig. (2-tailed)	.000		.000	.800
	N	500	500	500	500
[PRODUCTIONFLEX13LIK14SEV] How Likely and Severely is Production	Pearson Correlation	.251**	.254**	1	.039
	Sig. (2-tailed)	.000	.000		.386
	N	500	500	500	500
	Sig. (2-tailed)	.982	.800	.386	

Flexibility Affected by Communication Throughout the Supply Chain?]	N	500	500	500	500

**. Correlation is significant at the 0.01 level (2-tailed).

Table 12 Correlation Between Production Flexibility Variables and Communication/Knowledge Transfer

Correlations

		[PRODUCTIONFLEX5LIK6SEV] How Likely and Severely is Production Flexibility Affected by Labor Shortages?	**[PRODUCTIONFLEX7LIK8SEV]** How Likely and Severely is Production Flexibility Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	**[PRODUCTIONFLEX13LIK14SEV]** How Likely and Severely is Production Flexibility Affected by Communication Throughout the Supply Chain?]	**[COMMUNICATION]** During the Pandemic, the Firm Faced Challenges in Process Cycle Times and Production Flexibility as a Result of Poor Communication Throughout the Supply Chain.
[PRODUCTIONFLEX5LIK6SEV] How Likely and Severely is Production Flexibility Affected by Labor Shortages?	Pearson Correlation	1	.288**	.251**	.060
	Sig. (2-tailed)		.000	.000	.177
	N	500	500	500	500
[PRODUCTIONFLEX7LIK8SEV] How Likely and Severely is Production Flexibility Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	Pearson Correlation	.288**	1	.254**	.110*
	Sig. (2-tailed)	.000		.000	.014
	N	500	500	500	500
[PRODUCTIONFLEX13LIK14SEV] How Likely and Severely is Production Flexibility Affected by Communication Throughout the Supply Chain?]	Pearson Correlation	.251**	.254**	1	-.023
	Sig. (2-tailed)	.000	.000		.612
	N	500	500	500	500
	Sig. (2-tailed)	.177	.014	.612	
	N	500	500	500	500

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 13 Correlation Between Cost Efficiency Variables and Raw Material Shortages

Correlations

		[COSTEFFICIENCY7LIK8SEV] How Likely and Severely is Cost Efficiency Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	**[COSTEFFICIENCY9LIK10SEV]** How Likely and Severely is Cost Efficiency Affected by Alternative Suppliers?	**[COSTEFFICIENCY15LIK16SEV]** How Likely and Severely is Cost Efficiency Affected by Third Party/Stakeholder Involvement?	**[RAW MATERIAL SHORTAGES]** During the Pandemic, the Shortages of Raw Material in the Supply Chain Have Resulted in Cost Increase.
[COSTEFFICIENCY7LIK8SEV] How Likely and Severely is Cost Efficiency Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	Pearson Correlation	1	.243**	.295**	.026
	Sig. (2-tailed)		.000	.000	.569
	N	500	500	500	500
[COSTEFFICIENCY9LIK10SEV] How Likely and Severely is Cost Efficiency Affected by Alternative Suppliers?	Pearson Correlation	.243**	1	.268**	-.016
	Sig. (2-tailed)	.000		.000	.726
	N	500	500	500	500
[COSTEFFICIENCY15LIK16SEV] How Likely and Severely is Cost Efficiency Affected by Third Party/Stakeholder Involvement?	Pearson Correlation	.295**	.268**	1	-.062
	Sig. (2-tailed)	.000	.000		.168
	N	500	500	500	500
	Sig. (2-tailed)	.569	.726	.168	
	N	500	500	500	500

**. Correlation is significant at the 0.01 level (2-tailed).

Table 14 Correlation Between Cost Efficiency Variables and Communication/Knowledge Transfer

Correlations

		[COSTEFFICIENCY7LIK8SEV] How Likely and Severely is Cost Efficiency Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	**[COSTEFFICIENCY9LIK10SEV]** How Likely and Severely is Cost Efficiency Affected by Alternative Suppliers?	**[COSTEFFICIENCY15LIK16SEV]** How Likely and Severely is Cost Efficiency Affected by Third Party/Stakeholder Involvement?	**[COMMUNICATION]** During the Pandemic, the Firm Faced Challenges in Process Cycle Times and Production Flexibility as a Result of Poor Communication Throughout the Supply Chain.
[COSTEFFICIENCY7LIK8SEV] How Likely and Severely is Cost Efficiency Affected by Raw Material/ Component Shortages (Critical Materials/ Components)?	Pearson Correlation	1	.243**	.295**	-.135**
	Sig. (2-tailed)		.000	.000	.002
	N	500	500	500	500
[COSTEFFICIENCY9LIK10SEV] How Likely and Severely is Cost Efficiency Affected by Alternative Suppliers?	Pearson Correlation	.243**	1	.268**	.051
	Sig. (2-tailed)	.000		.000	.253
	N	500	500	500	500
[COSTEFFICIENCY15LIK16SEV] How Likely and Severely is Cost Efficiency Affected by Third Party/Stakeholder Involvement?	Pearson Correlation	.295**	.268**	1	.008
	Sig. (2-tailed)	.000	.000		.851
	N	500	500	500	500
	Sig. (2-tailed)	.002	.253	.851	
	N	500	500	500	500

**. Correlation is significant at the 0.01 level (2-tailed).

4.2.3.1 Elaborating the Correlation Results

Correlation is an analytical approach that studies the strength of relationships between two continuous and numerically measured variables. Correlation is related to covariance since the latter assesses the type of interaction between two specific variables while the former evaluates the strength and direction of such relationships. Thus, correlation is a more precise approach compared to covariance since it studies both the direction and strength of the observed/implied variable relationships. It eliminates the lack of standardization of values in covariance estimates by scaling the outcomes between -1 and +1. However, determining the covariance magnitude between two variables (i.e., whether the covariance is small or large) is essential when developing correlations by first assessing the covariances relative to the standard deviations of the two variables in question. Accordingly, the covariances must be normalized by dividing them with the standard deviations of the two variables, thereby creating the respective correlations between variable sets. The outcome of this process, the correlation coefficient, entails a metric that is dimensionless and ranging in value between -1 and +1 (Aryadoust & Raquel, 2020; Byrne, 2010). Coefficients that are closer to -1 or +1 are indicative of closer correlations between the variables. When there is no specific relationship between variables, 0 correlation coefficients may be observed (but a zero value would highlight the lack of a linear relationship). Positive correlation coefficients indicate that an increase in one variable has a similar incremental effect on the other variable, while negative values highlight an inverse relationship, whereby an increase in one variable decreases the value of the other.

The correlation results highlighted both negative and positive coefficients for the three primary variables, indicative of positive/constructive and inverse relationships. For the Cycle Times variables, there was no significant correlation between the sub-variables (i.e., CYCLETIME4SEV, CYCLETIME5LIK6SEV, and CYCLETIME7LIK8SEV). Additionally, there was no significant correlation between these sub-variables and the Communication (knowledge transfer) variable (see Table 10) and raw material shortages (see Table 9). The only positive correlation was between CYCLETIME7LIK8SEV (How likely and severely are cycle times affected by raw material/ component shortages?) and Communication, meaning that raw material/component shortages and communication ineffectiveness jointly impacted cycle times outcomes, albeit not significantly. However, the loadings on all correlation coefficients are quite lower than the ideal threshold of -1 or +1 (whereby the lowest and highest negative correlation coefficient was -.010 (CYCLETIME7LIK8SEV <<->> Raw Material Shortages), while the highest positive correlation had a coefficient of .049 – CYCLETIME4SEV <<->> Communication) (see Table 9 and 10). These correlation coefficients are quite low from the ideal threshold values. Referring to the correlation outcomes in both tables, the non-significant p-values are indicative of why these correlation estimates are quite low. Thus, these correlations indicate that raw material shortages and communication did not have significant causal effects on Cycle Times aspects in the engineering manufacturing sector.

The correlation coefficients between production flexibility variables and raw material shortages and communication effectiveness had a mixture of positive and inverse relationships. Table 10 highlights the correlations between the production flexibility variables and between these variables and raw material shortages. Highly significant positive relationships were observed between [PRODUCTIONFLEX5LIK6SEV] and [PRODUCTIONFLEX7LIK8SEV] (.288** at p<0.01), [PRODUCTIONFLEX5LIK6SEV] and [PRODUCTIONFLEX13LIK14SEV] (.251** at p<0.01), and between [PRODUCTIONFLEX7LIK8SEV] and [PRODUCTIONFLEX13LIK14SEV] (.254** at p<0.01) (see Table 11), meaning that the impacts of labor shortages on production flexibility were significantly linked to the impact of raw material/component shortages and communication. However, there was an inverse but insignificant relationship between raw material shortages and production flexibility aspects such as labor shortages and a positive but insignificant relationship between raw material shortages and Communication. There was a positive significant relationship between communication and the impact of production flexibility's association with raw material shortages (see Table 12), meaning that effective communication is a pivotal factor in improving production flexibility aspects in engineering manufacturing.

The Cost Efficiency produced correlations with varying levels of significance, (see Tables 13 and 14). The correlations between raw material shortages and the cost efficiency variable had one positive outcome (COSTEFFICIENCY7LIK8SEV << - >> Raw Material Shortages) and two inverse outcomes (COSTEFFICIENCY9LIK10SEV << - >> Raw Material Shortages) and (COSTEFFICIENCY15LIK16SEV << - >> Raw Material Shortages). This means that raw material shortages mostly had a negative impact on the cost efficiencies, especially when third parties/stakeholders and alternative suppliers were involved (see Table 13). On the other hand, there was a significant inverse relationship between communication effectiveness and cost efficiency outcomes in the event of raw material shortages, meaning that ineffective communication could have significantly impacted raw material availability, thereby increasing costs (see Table 14).

4.3 Research Results Comparison and Discussion

The study yielded three latent constructs each for the three dependent variables (i.e., Cycle Times, Production Flexibility, and Cost Efficiency, respectively, i.e., Tables 6, 7, and 8). The correlations had a mixture of positive and inverse correlations between the dependent variables (i.e., Cycle Times, Production Flexibility, and Cost Efficiency) and the independent variables (i.e., Raw Material Shortages and Communication). There was also a mixture of significant and insignificant positive and inverse relationships between these variables. Therefore, these findings can be interpreted as communication and raw material shortages having varied influences on the cycle times, production flexibility, and cost efficiency aspects in engineering manufacturing. This means that while there were different levels of severity and likelihood of supply chain disruptions such as raw material/component shortages, labour shortages, and communication throughout the supply chain, they had varied impacts or influence on each other during the pandemic period.

The Production Flexibility correlations (Tables 11 and 12) highlighted significant correlational outcomes between the latent variables (i.e., between labour shortages, raw material/component shortages, and communication). With significant correlations between these variables, these results indicate that the correlations between the variables were significant enough to impact most aspects regarding production flexibility within the firm, thereby affecting overall productivity during the pandemic period (Alkahtani et al., 2021). Therefore, it is clear that production flexibility was significantly impacted by all the assessed forms of supply chain disruptions at the organization.

The Cost Efficiency correlations (Tables 13 and 14) had varying levels of significance in the correlation estimates. Therefore, like the production flexibility outcomes, it is evident that supply chain disruption factors including raw material/component shortages and communication influenced the cost efficiencies involved in dealing with alternative suppliers and third party/stakeholder involvement, thereby impacting the firm considerably. Therefore, the study effectively answers the first research question, indicating varied correlation outcomes between supply chain disruption factors and their influence on cycle times, production flexibility, and cost efficiency in the engineering manufacturing sector. The results further indicate that the effectiveness of management processes linked with these primary variables were significantly affected during the COVID-19 period, which conforms with multiple research studies (Alkahtani et al., 2021; Farooq et al., 2021; Kunovjanek & Wankmüller, 2020). Thus, these three primary variables must be considered by organizations during pandemics or disasters.

Communication is recognized as a pivotal factor in the Cycle Times and Production Flexibility aspects, whereby the latent variables in the respective aspects recorded above average factor loadings with the associated observed variables. While the correlations for Cycle Times aspects do not show significant outcomes for both communication and raw material shortages, the Production Flexibility correlations indicate highly significant outcomes for the variables, alongside positive correlations with other latent variables such as labor shortages. Therefore, for research question two, it is evident that Communication could have a major (if not significant) impact on cycle times and production flexibility during the pandemic period for engineering manufacturing organizations.

The COVID-19 pandemic placed major disruptions on the smooth running of logistical and supply chain operations, whereby most manufacturers were forced to either close down their plants or operate at a minimized or scaled-down capacity. Farooq et al. (2021) stipulates that strategic decision-making and the integration of technologies to streamline affected processes in SCM were necessary for the survival of firms. Additionally, drastic changes in distribution and procurement, resource allocation, decision-making, emergency response, and other core aspects of SCM meant that Communication approaches had to be revised in firms keen on maintaining or managing a certain level of management effectiveness and performance (through mechanisms such as flexible production and optimized cycle times) (Anparasan & Lejeune, 2018; Govindan, Mina & Alavi, 2020; Ivanov & Das, 2020). Accordingly, organizations within the engineering manufacturing sector should devise actionable approaches that improve Communication during situations such as epidemics to minimize the negative impact on process outcomes, such as production flexibility and cycle times.

Finally, based on current literature and the study findings, it is evident that cost efficiency depends on cycle times and production flexibility. This means that optimized cycle times can influence/significantly lower production costs, thereby enhancing cost efficiency. Also, with flexible production (production flexibility), the firm can significantly lower costs through approaches such as scaling production (to cut back on unnecessary costs - such as power and storage/warehousing) depending on demand and supply, among other reasons. The study by Suleiman, Huo and Ye (2021) investigated the association between supplier just-in-time (JIT) practices (cost efficiency) and production/performance flexibility alongside human resource empowerment (EMP) and additive manufacturing technologies (AMT) – both representing cycle times. The researchers found out that the cycle times variables (AMT and EMT) worked alongside production/performance flexibility to improve cost efficiencies with JIT. On the other hand, Fragapane et al. (2020) stipulate that production flexibility enhances an organisation's capacity to have prompt reaction times (i.e., cycle times) with changing consumer demands, thereby significantly lowering cost expenditures with such changes. Fera et al. (2019) also report that production process optimization (that is, production flexibility) is crucial for manufacturing firms since it improves cycle times while cutting down on related costs. Thus, a flexible production line can have a major influence on cost efficiency.

CHAPTER FIVE: RESEARCH CONCLUSION AND RECOMMENDATIONS

This study investigates the impact of COVID-19 disruption on supply chain performance in the engineering manufacturing sector; examining the effective process performance presented by dependent variables and sub-variables. The approach embodied in this research was aimed at helping management in engineering manufacturing firms make evidence-based decisions when tackling or mitigating supply chain disruptions during disasters, and for improving or managing process effectiveness (cycle times, production flexibility, and cost efficiency) during disasters/pandemics with the consideration of various factors such as communication throughout the supply chain, automation, and mitigating raw material shortages, labour shortages, access restriction, Communication, demand fluctuations, alternative suppliers, and third party/stakeholder involvement. 500 participants were included in the study based on how long they had worked in the organization/industry. Other demographics assessed included age group (with most respondents aged between 24 and 40), gender (whereby 97.4% were male), education (with 46.6% having a college degree). The study aimed at addressing two research questions:

i. Do the current disruptions in the supply chain caused by Covid-19 pandemic including raw material shortages have a significant impact on the effective management process performance (cycle times, production flexibility, and cost efficiency) in the engineering manufacturing sector?
ii. Does Communication throughout the supply chain has a significant impact on the effective management process performance aimed at addressing the issues caused by supply disruptions (cycle times, production flexibility, and cost efficiency) in engineering manufacturing industry during the coronavirus pandemic?

To address these research questions, the following aims framed the study:

i. To help management in engineering manufacturing firms make evidence-based decisions when tackling or mitigating supply chain disruptions during disasters/pandemics.
ii. To recommend ways of improving or managing process effectiveness (cycle times, production flexibility, and cost efficiency) during disasters/pandemics with the consideration of various factors such as Communication throughout the supply chain and mitigating Raw material shortages.

The study responds to these research questions by indicating that there were varied correlation outcomes between supply chain disruption factors and their influence on cycle times, production flexibility, and cost efficiency in the engineering manufacturing sector. The results further indicate that the effectiveness of management processes linked with these primary variables were significantly affected during the COVID-19 period, which conforms with multiple research studies. On the second research question, the investigator concluded that Communication could have a major (if not significant) impact on cycle times and production flexibility during the pandemic period for engineering manufacturing organizations. These results also conform with current literature which largely posits that strategic decision-making and the integration of technologies to streamline affected processes in SCM were necessary for the survival of firms. Additionally, drastic changes in distribution and procurement, resource allocation, decision-making, emergency response, and other core aspects of SCM meant that Communication approaches had to be revised in firms keen on maintaining or managing a certain level of management effectiveness and performance (through mechanisms such as cost efficiency, flexible production, and optimized cycle times).

Based on current literature and the study findings, it is evident that cost efficiency depends on cycle times and production flexibility. This creates an interrelationship between the three primary variables as indicated on the study's conceptual framework, meaning that optimized cycle times can influence/significantly lower production costs, thereby enhancing cost efficiency. Also, with flexible production (production flexibility), the firm can significantly lower costs through approaches such as scaling production (to cut back on unnecessary costs - such as power and storage/warehousing) depending on demand and supply, among other reasons. The correlation between the dependent and independent variables in this study also contributes to answering the research questions by indicating how supply chain disruptions have impacted production flexibility and cycle times, thereby adversely affecting cost efficiency at the firm, which translates into ineffective management process performance. Also, poor communication in the supply chain causes lack of proper planning to ensure production flexibility and efficient cycle times, thereby causing inadvertent increases on production costs (i.e., poor cost efficiency). Accordingly, these outcomes meet the research objectives, including guiding the management in engineering manufacturing firms make evidence-based decisions when tackling or mitigating supply chain disruptions during disasters/pandemics and developing recommendable approaches for improving or managing process effectiveness (cycle times, production flexibility, and cost efficiency) during disasters/pandemics with the consideration of various factors such as Communication throughout the supply chain and mitigating Raw Material Shortages, considering the illustrated correlation of the three variables. Thus, a flexible production line in the manufacturing plant can have a major influence on cost efficiency.

5.1 Research Limitations and Strengths

Several issues emerged that limit the current study, thereby making them worth considering. Firstly, the study may not be considered as representative of the wider engineering manufacturing industry since data was collected from only one organization. However, it can be argued that the large data size (n = 500) imbues some form of representation for the broader engineering manufacturing sector. Secondly, the study is limited to three primary variables (cycle times, production flexibility, and cost efficiency), but other industries or firms may consider a wider array of variables that were significantly impacted by supply chain disruptions during the COVID-19 period, such as the roll-out and implementation of automation and the availability of the necessary SC infrastructure during such pandemics.

While the study bears various limitations, there are also some strengths that contribute to current literature and managerial practices. From a management perspective in the engineering manufacturing sector, this study presents strategic managerial information regarding pivotal areas that firms should strengthen and implement resilience mechanisms to prevent major disruptions during similar pandemics or disasters. SC disruptions, such as demand fluctuations, the lack of automation, raw material/component shortages, poor or inadequate communication within the supply chain, dealing with alternative suppliers, labour shortages, access restriction, and third-party/stakeholder involvement have a significant impact on either of the three aspects that directly influence organizational performance, that is, cycle times, production flexibility, and cost efficiency. Therefore, management in the engineering manufacturing sector can apply this knowledge through strategic decision-making to develop tailored mechanisms that reduce the impact of such disruptions in their firms in the future, thereby bolstering organizational resilience to pandemics or similar disasters. This stipulation can also be considered as a strength of the study, since it addresses the first objective of this research: to help the management in engineering manufacturing firms make evidence-based decisions when tackling or mitigating supply chain disruptions during disasters/pandemics.

5.2 Recommendations and Future Research

To address the second objective of the study (i.e., identifying ways of improving or managing process effectiveness (cycle times, production flexibility, and cost efficiency) during disasters/pandemics with the consideration of various factors such as Communication throughout the supply chain and mitigating raw material shortages), this study proposes various recommendations:

Firstly, firms in the engineering manufacturing sector should consider approaches that minimize the impact of supply chain disruptions during epidemics or similar disasters on their production processes such as cycle times, production flexibility, and cost efficiency. Accordingly, more research and application should be conducted on operational flexibility that can effectively handle uncertain SC aspects during such uneven times. With optimized operational flexibility, firms can efficiently hedge customer demand variability during pandemics, whereby production levels are attuned to the current demands, thereby creating satisfaction to the closer/priority clientele or to critical/high-margin products. The approach also means that firms in the sector can effectively scale their cycle times according to the changing demand cycles, ultimately improving their cost efficiency outcomes.

Secondly, this study recommends the widespread adoption of industry 4.0 technologies to fill in the gaps caused by SC disruptions during pandemics. Such technologies can be used to safeguard against the discussed SC disruptions and their impact on organizational processes by developing smart factories, smart logistical/ warehousing techniques, smart SCs, and smart materials. The adoption of these lucrative technologies can be scaled to meet the specific cycle time, flexibility, and cost effectiveness needs (among others) of both medium and large-scale manufacturers across the sector. Technological adoption during pandemic periods could be highly lucrative for manufacturing organizations since it presents an opportunity to enhance and optimize entire supply chain networks, production systems, and material quality and management. Furthermore, integrating technologies such as artificial intelligence (AI), virtual reality (VR) processes, machine learning (ML), and the Internet of Things (IoT) can cut-back on the inefficiencies found in supply chains, thereby making SCs more efficient, profitable, optimized, risk-free, and transparent, aspects which bolster organizational or supply chain resilience during pandemics or disasters. However, thorough needs assessments should be conducted by every engineering manufacturer before considering and implementing any Industry 4.0 aspect/technology. Ultimately, optimal technological adoption can drastically reduce supply chain disruption effects on cycle times, production flexibility, and cost efficiency in engineering manufacturing firms.

Thirdly, based on current literature and the study findings, it is evident that cost efficiency depends on cycle times and production flexibility. Thus, it is recommended that firms in the engineering manufacturing sector optimise their cycle times to significantly lower production costs, thereby enhancing cost efficiency. Furthermore, it is recommended that manufacturers in the industry should maximise production flexibility to help the firm to significantly lower costs through approaches such as scaling production (to cut back on unnecessary costs - such as power and storage/warehousing) depending on demand and supply, among other reasons. Therefore, a flexible production line in the manufacturing plant can have a major influence on cost efficiency.

Future studies should research how the integration of specific production technologies influence the impact of supply chain disruptions on organizational processes and performance outcomes in the long-term. Additionally, researchers can establish new interrelations between this study's variables (and new variables) based on their impact on supply chain disruptions and organizational performance outcomes. These research metrics can be pivotal in determining the robustness and resilience of company supply chains in the sector during the current and future crises and establish mechanisms for sustainability and growth during such periods.

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APPENDIX I: CODEBOOK FOR DATA ENTRY

Supply Chain Disruptions: Codebook for Data Entry

Item	Variable Code	Response(s) Code(s)	Compliance Supporting Answers
1. Age group? (Fink, 2003)	AGEGRP	1 = Under 18 2 = 18-24 3 = 24-40 4 = 40-60 5 = Over 60	NA
2. What is your gender? (Fink, 2003)	GENDER	1 = Male 2 = Female	NA
3. How long have you been working at this plant/organization/industry? (Fink, 2003)	POSLNGTH	1 = Less than 3 years 2 = 3-5 years 3 = 5-7 years 4 = 7-10 years 5 = Over 10 years	NA
4. Educational status (Fink, 2003)	EDUC	1 = High school 2 = College degree 3 = Bachelor's degree 4 = Master's degree 5 = PhD or higher	NA
Cycle Times			
5. How severely are cycle times affected by storage and access restrictions? (Butt, 2021)	CYCLETIME4SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
6. How likely are cycle times affected by labor shortages? (Ambrogio et al., 2022)	CYCLETIME5LIK	1 = Very unlikely 2 = Unlikely 3 = Neutral 4 = Likely 5 = Very likely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
7. How severely are cycle times affected by labor shortages? (Ambrogio et al., 2022)	CYCLETIME6SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5

8. How likely are cycle times affected by raw material/component shortages (critical materials/components)? (Kapoor et al., 2021; Zhu et al., 2020)	CYCLETIME7LIK	1 = Very unlikely 2 = Unlikely 3 = Neutral 4 = Likely 5 = Very likely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
9. How severely are cycle times affected by raw material/component shortages (critical materials/components)? (Kapoor et al., 2021; Zhu et al., 2020)	CYCLETIME8SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
Production Flexibility			
10. How likely is production flexibility affected by labor shortages? (Okorie et al., 2020; Siagian et al., 2021)	PRODUCTIONFLEX5LIK	1 = Very unlikely 2 = Unlikely 3 = Neutral 4 = Likely 5 = Very likely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
11. How severely is production flexibility affected by labor shortages? (Okorie et al., 2020; Siagian et al., 2021)	PRODUCTIONFLEX6SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
12. How likely is production flexibility affected by raw material/component shortages (critical materials/components)? (Okorie et al., 2020; Siagian et al., 2021)	PRODUCTIONFLEX7LIK	1 = Very unlikely 2 = Unlikely 3 = Neutral 4 = Likely 5 = Very likely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
13. How severely is production flexibility affected by raw material/component shortages (critical materials/components)? (Okorie et al., 2020; Siagian et al., 2021)	PRODUCTIONFLEX8SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5

14. **How likely is production flexibility affected by Communication throughout the supply chain?** (Yawson, 2020; Zimmerling & Chen, 2021)	PRODUCTIONFLEX13LIK	1 = Very unlikely 2 = Unlikely 3 = Neutral 4 = Likely 5 = Very likely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
15. **How severely is production flexibility affected by Communication throughout the supply chain?** (Yawson, 2020; Zimmerling & Chen, 2021)	PRODUCTIONFLEX14SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
Cost Efficiency			
16. **How likely is cost efficiency affected by raw material/component shortages (critical materials/components)?** (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	COSTEFFICIENCY7LIK	1 = Very unlikely 2 = Unlikely 3 = Neutral 4 = Likely 5 = Very likely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
17. **How severely is cost efficiency affected by raw material/component shortages (critical materials/components)?** (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	COSTEFFICIENCY8SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
18. **How likely is cost efficiency affected by alternative suppliers?** (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	COSTEFFICIENCY9LIK	1 = Very unlikely 2 = Unlikely 3 = Neutral 4 = Likely 5 = Very likely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5

19. How severely is cost efficiency affected by alternative suppliers? (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	COSTEFFICIENCY10SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
20. How likely is cost efficiency affected by third party/stakeholder involvement? (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	COSTEFFICIENCY15LIK	1 = Very unlikely 2 = Unlikely 3 = Neutral 4 = Likely 5 = Very likely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
21. How severely is cost efficiency affected by third party/stakeholder involvement? (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	COSTEFFICIENCY16SEV	1 = Mild 2 = Moderate 3 = Neutral 4 = Severely 5 = Very severely	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
Ratings			
22. During the peak of the pandemic, the firm could not meet all its supply orders in time as a result of supply chain fragility. (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	RATE1ORDERSANDTIME	1 = Strongly disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly Agree	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
23. During the pandemic, the firm faced challenges in process cycle times and production flexibility as a result of poor Communication throughout the supply chain. (Eldem et al., 2022; Larrañeta et al., 2020; Magableh,	RATE2KNOWLEDGETR	1 = Strongly disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly Agree	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5

2021; Rapaccini et al., 2020)			
24. The firm/plant is determined to invest more in technological innovation after being better aware of the firm's self-development problems during the pandemic. (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	RATE3INVESTTECH	1 = Strongly disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly Agree	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5
25. During the pandemic, the shortages of raw material in the supply chain have resulted in cost increase. (Eldem et al., 2022; Larrañeta et al., 2020; Magableh, 2021; Rapaccini et al., 2020)	RATE4MATERIALANDCOST	1 = Strongly disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly Agree	1 = 1 2 = 2 3 = 3 4 = 4 5 = 5

0 = indicates no response to item

Demographic information [4 COLUMNS IN EXCEL]

Module 1: Cycle Times [5 COLUMNS IN EXCEL]

Module 2: Production Flexibility [6 COLUMNS IN EXCEL]

Module 3: Cost Efficiency [6 COLUMNS IN EXCEL]

Module 4: Ratings [4 COLUMNS IN EXCEL]

Key to the Codes

- For each of the three primary variables (Cycle Times, Production Flexibility, and Cost Efficiency), the each of the latent variables are numbered from 1-6, depending on the variable.
- Accordingly,
    - CYCLETIME1LIK assesses the likelihood aspect
    - CYCLETIME2SEV assesses the severity aspect
    - And so on.
- For the Ratings, each variable is labelled according to the questionnaire question as indicated.