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Pandemic Effect on the Industry 4.0 Readiness: A Case Study in Vietnamese Industry

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Abstract: The COVID-19 pandemic has seriously affected the global supply chain because many links in the chain have been broken or severely delayed. Different epidemic response policies from other countries also have had a significant impact on logistics activities and the operations of businesses. The considerable influence of this pandemic also has caused companies to change their strategies for risk management and apply advanced technologies to handle disruption in the future. This study explores the pandemic's impact on the decision to apply Industry 4.0 technology in the production process using qualitative research. The leaders from 4 selected manufacturing firms were interviewed with open-end questions and thematic and cross-case analyses were applied to analyze their strategic orientation to use Industry 4.0 technology in their businesses during and after COVID-19. The results show that COVID-19 influenced the decision to implement Industry 4.0 technology in international and local companies within the global market. In contrast, the pandemic has not affected the decision to implement Industry 4.0 technology in a local company with a local market. The following policy recommendations are based on these findings. The government should establish a policy to provide vital support to local SMEs because their employee capability is too low to implement Industry 4.0 technology and deal with the pandemic crisis. Moreover, executive training for giving essential knowledge for Industry 4.0 should be provided to the owners of SMEs.

Keywords: COVID-19, risk management, industry 4.0 readiness, leadership, business continuity plan.

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1. Introduction

Since the end of 2019, the COVID-19 pandemic has existed globally, creating a multi-dimensional crisis affecting many different industries and people's material and spiritual lives. The pandemic has caused unprecedented adverse effects in Vietnam and worldwide.

The pandemic appeared in Vietnam in early 2020 and there have been 4 outbreaks so far (Le, 2021). May of 2022, the total number of cases in this country has reached more than 10.5 million people. Vietnam has taken strong epidemic prevention measures, including closing and blocking provinces and cities with infected people to protect people from the spread of the disease. The blockade of cities simultaneously creates difficulties for businesses when the supply chain is broken, the logistics system is stagnant, and people are restricted from leaving their homes.

In Vietnam, COVID-19 has generated record numbers, but in a way no one wants. More than 1.7 million working-age people were unemployed in the third quarter of 2021, up by half a million compared to the previous quarter. The unemployment rate reached 3.98%, the highest in a decade, far surpassing the unemployment rate during other difficult periods of the economy. Twelve million people cut their working hours; 18.9 million people lost their income.

Factories had to close because of the epidemic. On average, about 9,700 businesses stop doing business or dissolve each month. Never before in history have more companies closed than were newly established. According to the Viet Nam General Statistics Office, this data may not fully reflect reality.

After the first three outbreaks of the disease, the epidemic control situation in Vietnam was better when the vaccine coverage rate increased, and the distancing orders were eased. Businesses also started to return to normal production and business activities. However, not all companies have come back strongly due to the severe damage caused in nearly 2 years of the epidemic.

Industry 4.0, or the Fourth Industrial Revolution, is the digital transformation of traditional industrial and manufacturing activities using intelligent and modern technology to deliver real-time decision-making and enhanced productivity. These new technologies could increase production efficiency while better connecting with supply chain partners and reducing dependence on direct labor. The Vietnamese Ministry of Industry and Trade investigated enterprises' readiness to implement Industry 4.0 in Vietnam in February 2019. The survey was randomly distributed to 14,666 companies, and there were 2,569 responses. The results show that most industrial enterprises in Vietnam (85%) are considered "Outsiders" who are not prepared to participate in the Fourth Industrial Revolution. A small number (13%) are at the "Beginner" level, which means companies have pilot initiatives for Industry 4.0. The remaining enterprises are 2% at the "Intermediate level," which means companies set up Industry 4.0 in their strategies, and there is some partial automation in the collection of data. There is 1% at the "Experienced" level, which means only a few companies have an Industry 4.0 strategy formulated with some investment budgets. There is some essential preparation for Industry 4.0, and companies' employees have adequate skill levels in some relevant areas of Industry 4.0 infrastructure.

Leaders' strategy in applying Industry 4.0 technology in their production process may change after the epidemic. This study aims to identify the effect of COVID-19 on Industry 4.0 readiness. The study also explores the perception of business leaders about the need for business continuity management (BCP) policies to respond to future risks promptly.

2. Literature Review

2.1. COVID–19 Pandemic and Its Effect on Manufacturing Enterprises

The COVID-19 pandemic has been sweeping the world, causing unprecedented negative impacts on the world economy and Vietnam. The COVID-19 epidemic is still developing in many countries worldwide, negatively affecting significant economies. When countries apply different social distancing measures, production efficiency often will be reduced, causing difficulties for the global supply chain and affecting the global value chain.

Chowdhury et al. (2021) indicated that a pandemic negatively impacts firm performance and efficiency. Meanwhile, Seetharaman (2020) believes that the world economy will face the biggest problem of supply shortage when an epidemic occurs. Moreover, many studies confirmed that COVID-19 has a much more severe impact on the economy than previous epidemics, such as SAR in 2003 (Koonin, 2020). During the epidemic period, almost all supply chain members were affected (Paul and Chowdhury, 2020), leading to a series of businesses facing financial difficulties and disruptions in their supply chain response (Dontoh et al., 2020).

The outbreak of COVID-19 caused the demand for essential products to increase, causing a severe supply shortage (Deaton, 2021; Govindan et al., 2020; Gunessee and Subramanian, 2020; Hakovirta and Denuwara, 2020). The outbreak led to shortages of essential products and prolonged the transit time of goods throughout the supply chain (Ivanov, 2020). Iyengar et al. (2020) pointed out the impact of COVID-19 on the production management of enterprises, while essential products are in severe shortage, and non-essential products are backlogged.

Meanwhile, the demand for non-essential products has fallen sharply, causing an imbalance in the global economy (Abhishek et al., 2020; Chiaramonti and Maniatis, 2020; Derevyankina and Yankovskaya, 2020). The pandemic has caused instability in demand, thereby affecting enterprises' supply chain management and demand forecasting process. (Gunessee and Subramanian, 2020). In addition, the epidemic response measures of the governments of different countries have caused labor shortages for enterprises (Leite et al., 2020).

During the pandemic, transportation and logistics services have seriously disrupted the supply chain causing delays in the transportation and distribution of goods, especially in international trade (Chiaramonti and Maniatis, 2020; Choi, 2020; Dente and Hashimoto, 2020). Moreover, the COVID-19 epidemic has also caused a series of businesses to go bankrupt and stop production, including companies that are suppliers, distributors, retailers, and even manufacturers (Handfield et al., 2020).

2.2. Industry 4.0 Technologies and the Change of Operational Business Strategies to be Survival

The Industrial Revolution 4.0 is forecasted to change the entire production, management, and administration system worldwide, having a substantial impact on all aspects of life, economy, politics, society, state, governments, businesses, organizations, individuals, etc., and create a digital economy.

There are two layers of technologies 4.0; the first is called front–end technologies, including smart manufacturing, smart products, smart supply chain, and smart working. The second one is called base technologies, including the Internet of Things (IoT), cloud services, big data, and analytics (Alejandro et al., 2019).

However, there are significant challenges for companies to apply Industry 4.0 technology. The German Association of Mechanical Engineering (Verband Deutscher Maschinen-und Anlagenbau - VDMA) compiled a model to evaluate the readiness of companies for Industry 4.0. There are six dimensions in the model used to create six levels of Industry 4.0 readiness. The Industry 4.0 readiness model is shown in table 1.

The measurement of six dimensions helps the company evaluate its level of Industry 4.0 readiness. The six dimensions include employees, strategy and organization, smart factory, smart operation, smart product, and data-driven services. These six dimensions include eighteen other factors.

Many studies show that the application of Industry 4.0 technology in production and business will help increase the competitiveness of enterprises. The application of technology solutions in the company helps to shorten the time to deploy

administrative processes, save costs, and avoid errors caused by manual data entry, thereby focusing resources on improving products and services offered to customers (Dalenogare et al., 2018; Jabbour et al., 2018; Alejandro et al., 2019; Abdullah et al., 2022).

Table 1. The Industry 4.0 readiness model from the German Association of Mechanical Engineering (VDMA). (Source: Industrie 4.0 Readiness, 2015)

Strategy and organization	Strategy	Level 5	Top performer	Leaders
	Investments			
	Innovation management			
Smart factory	Digital modelling	Level 4	Expert	
	Equipment infrastructure			
	Data usage			
Smart operations	IT systems	Level 3	Experienced	
	Cloud usage			
	IT security			
	Autonomous processes	Level 2	Intermediate	Learners
	Information Sharing			
Smart products	Data analytics in the usage phase			
	ICT add–on functionalities	Level 1	Beginner	Newcomers
Data-driven services	Data-driven services			
	Share of revenues			
	Share of data used	Level 0	Outsider	
Employees	Skill acquisition			
	Employee skill sets			

Many published studies have shown how businesses change their strategies to recover during and after the pandemic. Among them, the most interesting method for changing how factories operate is applying digital technology and the production and management process (Moktadir et al., 2020; Mahmood, 2021; Mehrolia et al., 2021; Milne et al., 2021).

Manufacturing enterprises should apply digitalization in communication and smart operation strategies to gain a competitive advantage (Choi, 2020; Gurbuz and Ozkan, 2020). Businesses that want to operate sustainably need to invest more in information technology (Rowan and Laffey, 2020; Sharma et al., 2020; Van Barneveld et al., 2020; Van Hoek, 2020).

Meanwhile, Ivanov (2020) argued that automating the production process is the best way for manufacturing enterprises to survive sustainably and reduce the risks of production shutdown when similar situations, such as COVID-19, happen.

Businesses need to conduct business continuity plans (BCPs) during the new normal when COVID-19 cools down. Margherita and Heikkilä (2021) have provided a framework for applying BCP drawn from large companies globally. Having a sound BCP strategy will help businesses to stand firm and promptly cope with future risks (Sahebjamnia et al., 2018).

3. Research Method

This study explores the pandemic's impact on the strategy's decision to apply Industry 4.0 technology in the production process using qualitative research. The leaders from the selected firms were interviewed with open-ended questions- for example, the problems during each phase of the pandemic and the measures against the crisis. Moreover, Industry 4.0 readiness was assessed in each company. Then, the thematic and cross-case analyses were applied to analyze the risk management and their strategic orientation to use technology in their businesses.

The thematic analysis was applied through the following steps (Braun and Clarke, 2006), including familiarization, coding, generating themes, reviewing themes, defining and naming themes, and writing up the report. This research aimed to identify the influence of COVID-19 on Industry 4.0 strategic decisions and post-pandemic actions.

4. Case Studies

The four manufacturing companies in Vietnam, as shown in Table 2, were selected as a case study to assess the overall impact of the epidemic on manufacturing enterprises. Senior leaders of four manufacturing companies with different company sizes and manufacturing sectors were interviewed to understand the influence of the pandemic and their Industry 4.0 readiness. Moreover, these companies are in various supply chain types such as local-customer with local suppliers, international-customer with local

suppliers, and international-customer with international suppliers. With the different supply chain types, we are able to compare their customers' effect on the firms' resilience and Industry 4.0 readiness.

Company 1

The first case study is a Vietnamese company specializing in the production of edible sugar, established in 2001 with about 40 employees. The company's suppliers and customers are all local. Thus, the supply chain members are all domestic.

During the two years of the COVID-19 pandemic in Vietnam, amid four outbreaks, the company faced many difficulties in production. The company lacked around 50% of workers during the outbreak because of the high infection rate and the quarantine requirement of the government. The bans on people going out, medical isolation, and closure of infected localities caused the company's logistics system to be delayed, leading to an increase in the lead time of up to 30% compared to the rate before the pandemic.

The company's customers and suppliers were similarly affected by the epidemic, so the number of orders fell by 25% compared to the expected volume of orders before the pandemic. At the same time, there was up to a 50% shortage in raw materials.

The company faced severe effects in the first three-phase pandemic due to the lack of experience and lack of connection with state agencies. From the fourth phase of the epidemic in April 2021, the company operated more productively due to the high vaccine coverage rate, the lockdown ended, and the government became more open to disease prevention measures. During this time, the company's production efficiency increased by 50% compared to the outbreak's first phase.

After more than 2 years of the epidemic, the company is gradually recovering with an efficiency increase of 50% compared to the first outbreak. There was an increase in employees' and managers' ability to adapt to the new management system and work remotely. The company applied many measures to prevent disease, including working from home, holding online meetings, and social distancing. The company also required workers to stay over at the factory during the outbreak to avoid infection from outsiders.

Company 2

Company 2 is a medium-sized Vietnamese company with 50 employees, specializing in frozen seafood production; one hundred percent of its products are exported, mainly to the Japanese market. The company's suppliers are all local.

The company has obtained many quality certifications such as VietGap, GlobalGap, Best Aquaculture Practices Certified, and ASI Certified to satisfy the international market requirement. Therefore, its business depends on export logistics. However, during the epidemic, export logistics activities were interrupted, and freight ships trading between countries were restricted due to the government's quarantine and disease control orders, which seriously impacted the company's export situation.

During the first and second COVID-19 outbreaks in Vietnam, the company stopped production completely and filled existing orders with the inventory. Since the third outbreak in January 2021, the company has returned to work, but the productivity is only 20% of the pre-pandemic level. Moreover, orders also have dropped sharply. In addition, domestic materials are in severe shortage and it is estimated that the available raw materials can only meet about 20% of the needs of the company.

The company responded to COVID-19 quite negatively when it stopped production entirely during the first three phases. Office staff and management level worked at home, and all workers at the factory quit their job.

Company 3

Company 3 is a large company with foreign investment and many branches in different countries. The company specializes in manufacturing beverage cans and supplying them entirely to domestic customers. The company's unit in Vietnam has about 200 employees, established in 1993. Most of its customers are multinational companies with branches in Vietnam.

Despite being a large company and having a lot of experience in production and business, the company also faced many difficulties when the COVID-19 epidemic hit. It is estimated that the company lacked about 50% of workers during the outbreak because most were infected and trapped due to the state's isolation, blockade, and local closure orders. The number of orders dropped sharply in the first 3 outbreaks. In the 4th phase of the epidemic, the production volume of the enterprise increased significantly but the order volume was still 25% lower than before the pandemic.

Although raw materials are mainly sourced domestically, there is a severe shortage of raw materials due to the broken supply chain and the stagnation of the national logistics system. However, at the same time as the shortage of raw materials, the number of orders also decreased sharply, so the lack of raw materials did not affect the fulfillment of orders much. The strength of this business is its ability to recover relatively quickly. After the initial three outbreaks, it has recovered almost to the same level as before the epidemic. The company has flexibly applied many of the measures to deal with COVID-19 during an outbreak, such as requiring workers to stay at the factory during the outbreak, keeping distance between workers at the factory, connecting information between departments through software, and implementing alternate staffing plans.

Table 2. Characteristics of case studies

Characteristics of company	Company 1	Company 2	Company 3	Company 4
Year of Establishment	2001	2003	1993	2008
Number of employees	40	50	200	220
Company Size	Medium	Medium	Large	Large
Business Type	Manufacturing	Manufacturing	Manufacturing	Manufacturing
Firm type	Local	Local	Multinational	Multinational
Product	Sugar	Frozen seafood	Beverage cans	Petroleum jelly
Customers	Local	International	Local	International
Suppliers	Local	Local	Local and international	Local and international

Company 4

The fourth case study is a large company specializing in the production of lubricants and refined petroleum products. The company is a foreign-invested company whose products are mainly exported to foreign markets. The company established a branch in Vietnam in 2008 with a staff of about 220 people.

Typical of a company with a global supply chain, its raw materials are mainly imported from abroad, and its customers are also overseas. Therefore, during the pandemic, the company faced many logistics difficulties, from importing raw materials to delivering refined products to customers.

Unlike the companies mentioned above, the shortage of personnel has not been much of a problem because fewer workers are in the production lines. The company applies many modern lines and advanced technology in production, operation, and management.

However, the number of orders dropped sharply in the first 3 phases, leading to a sharp decrease in production. It is estimated that during the 2 years of the epidemic, the company's production volume was only about 40% compared to before the epidemic. The lead time was also extended by at least 30% due to movement restrictions and more cumbersome export procedures.

This case also demonstrates a business strength. It turned around very quickly after the fourth phase of the epidemic temporarily subsided, and the government's blockade and isolation orders were relaxed. The company's production efficiency has increased rapidly since the government imposed a new normal after the epidemic. Still, the efficiency level is only about 80% before the epidemic.

Because production is mainly based on automation and modern machines, production lines do not have too many workers, making it easier to apply epidemic prevention measures. The usual measures are used, such as disinfecting the workplace, requiring employees to wash their hands frequently, keeping a distance of 2 meters between workers, and performing frequent rapid tests of employees to ensure the isolation of the source of infection in the workplace.

5. Thematic Analysis

This section will be based on the interviewees' transcripts to find the similarities and dissimilarities. The thematic analysis defined the case study's code and theme, including four themes: the effect of COVID-19, the readiness level of using Industry 4.0, the leader's perspective, and difficulties.

Firstly, the impact of COVID-19 on business operations will be studied and compared to determine whether there is a difference between company size, product type, or supply chain scope in each case.

The second step is to analyze the level of readiness to apply Industry 4.0 technology in the production activities of enterprises. The readiness levels will be based on the methodology of the German Association of Mechanical Engineering (VDMA). Accordingly, 6 readiness levels will be assessed and divided into 3 groups, including the Newcomer group (levels 0 and 1: companies outside of Industry 4.0 and companies that are just starting to be interested in Industry 4.0 technology but have not taken any action yet), the Learning Group (level 2: companies that have basic qualifications with advanced technology and have learning activities about Industry 4.0 technology), and the Leading Group (levels 3-6: companies that have experience in applying Industry 4.0 technology to their production activities).

The third step considers the changes in business leaders' perception after the pandemic about applying technology to production and management to avoid the risks of production stoppage or shortage of workers and materials in factories. Also, this step explores the leaders' perspective on the post-pandemic actions, the application of business continuity management plans, and effective risk management. The last section is about the difficulties that businesses perceive when applying Industry 4.0 technology to their production and management processes. The results of the Thematic analysis are summarized in Table 3.

Thematic analysis

Table 3. Thematic analysis (Appendix 1)

6. Discussion and Cross-Case Analysis

This section will discuss and analyze the similarities and differences among the cases to identify the factors for manufacturing firms to be resilient and implement Industry 4.0 technology.

Local companies with local supply chains operating within a country will be less affected. Companies with global supply chains, overseas customers, or overseas suppliers will be more at risk due to countries' measures to prevent the spread of the disease.

Those using modern technology can recover better and faster than others. Companies that quickly adapt to the epidemic and restore production efficiency often have an existing contingency plan and have prepared in advance. Meanwhile, enterprises with a global supply chain faced more logistics risks than those with a local supply chain when the pandemic occurred. Company 1, with a local supply chain, faced a less severe shortage of materials than the others with global customers or suppliers.

All 4 cases faced a lack of employees during the pandemic. For case study 3, in level 2 of Industry 4.0 readiness, the lack of employees had a moderate effect. However, case study 4 applied modern technologies to their production process, and experienced less impact than the others.

Supply chain type is one of the key factors of responsiveness and the decision to implement Industry 4.0. Firms with the local supply chain recovered faster than those with the global supply chain. Firms that applied modern technologies fared better than those that did not.

The readiness to change and adapt is the key finding of the research paper. The larger the company, the greater the effects of COVID-19, and the higher the interest in changing to adapt. Companies with a local supply chain seem less receptive to change.

Leadership could be identified from the cases as one of the key factors. Deciding to use new technologies depends not only on the leaders' perspective but also on their company readiness and the difficulties they face. Firstly, leaders' decisions were affected by the COVID-19 pandemic. After the pandemic, leaders revealed their need for new technologies and changed their perspectives.

Company Industry 4.0 readiness level is another critical factor driving the decision to implement Industry 4.0. The case study analysis shows that international companies have higher "Industry 4.0" readiness because they have a higher budget and higher employee capability. In contrast, local companies have a lower level of Industry 4.0 readiness. However, a local company with an international market is more willing to adopt Industry 4.0 than one with a local market.

An aspect that limits the decision to apply Industry 4.0 technologies is difficulties in the system and workforce. The cost of new technologies is the real problem when the expense of applying new technologies is not a small amount. The investment expense will be a significant financial burden, especially for small and medium-sized companies. Operation workers and management skills in Industry 4.0 are also the main barriers to leaders' decisions. The application of 4.0 technology in production cannot proceed without skill training for operators and managers of enterprises.

Companies 3 and 4 had a BCP that could adapt better than the others when COVID-19 occurred; others that did not have any preventive plan fared worse when facing problems. Company 2 is an example of this issue; they closed all their production during the pandemic. Closing production can be seen as an adverse decision when there is a risk. Changes in planning for continuity management are also happening. While the large companies that already have experience in implementing BCPs continue to develop plans, the smaller ones are less concerned about the issue.

Figure 1 shows a conceptual diagram of the factors driving a company to use Industry 4.0. The results of the cross-case analysis are summarized in Table 4.

Cross–case analysis

Table 4. Cross-case analysis (Appendix 2)

7. Conclusion

The epidemic has seriously affected the performance of businesses in all areas around the world and caused negative impacts on global supply chains and value chains. Despite the enormous challenges faced, companies still have to survive and revive their operations. This research aimed to study the effect of the pandemic on leaders' decisions to apply Industry 4.0 technology to improve their production during and after the disease outbreak. The study was conducted based on interviews with 4 manufacturing companies in Vietnam. The thematic and cross-case analysis was applied to determine the factors.

The results show that COVID-19 influenced the decision to implement Industry 4.0 technology in international and local companies within the global market. In contrast, the pandemic did not affect the decision to implement Industry 4.0 technology in a local company with a local market. One of the primary reasons is that the international company has a higher Industry 4.0 readiness level than the local company. The multinational company has a higher investment budget and high employee capability. Moreover, there is a change in the perception of business leaders about applying Industry 4.0 technology to the production process to handle future risks. However, the perspective changes are different between leaders from local companies and international companies. While the leaders from global companies are aware of future risk management, the leaders from local companies seem less concerned about this issue.

In addition, manufacturing enterprises participating in the global supply chain have higher responsiveness because these international companies had their BCPs implemented before COVID-19. In contrast, the local companies are not aware of the BCPs.

For the policy recommendation, the government should establish a policy to provide vital support to local SMEs because their employee capability is too low to implement Industry 4.0 technology and deal with the pandemic crisis. Moreover, executive training for giving essential knowledge for Industry 4.0 should be provided to the owners of SMEs.

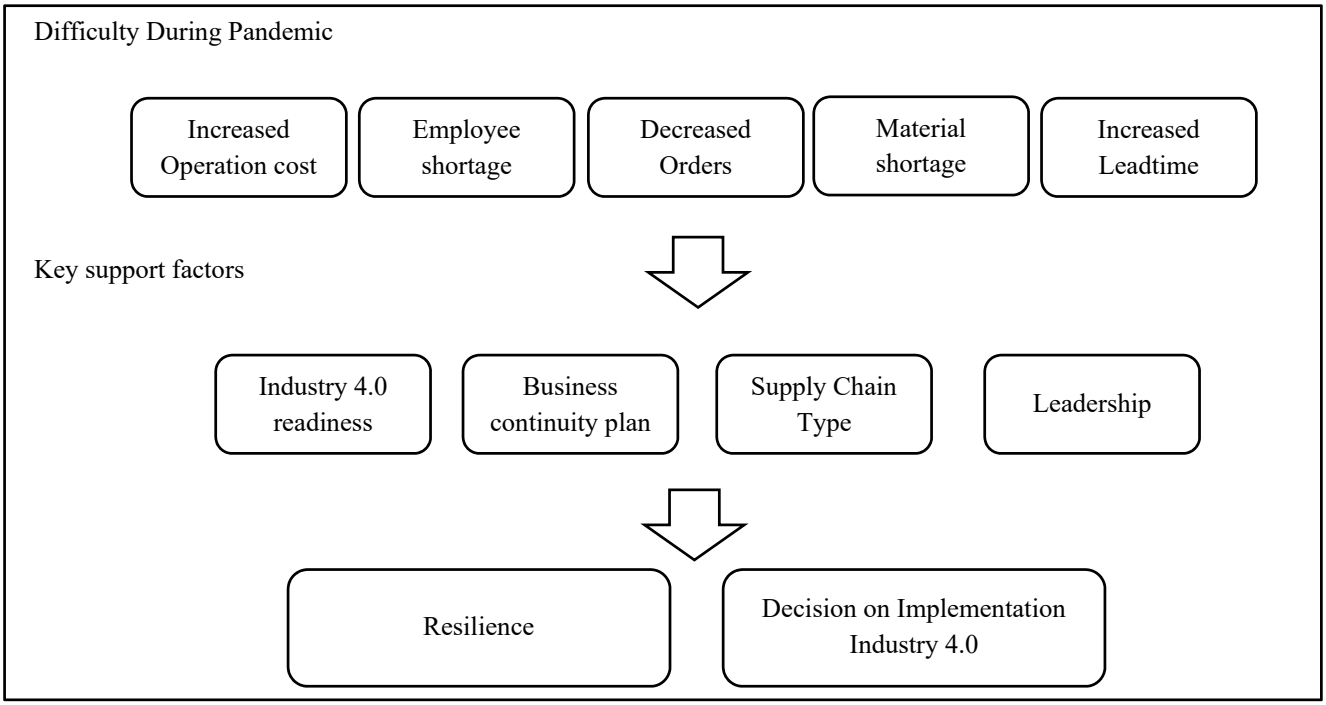

Fig 1. A conceptual framework for factors driving companies to implement Industry 4.0 technology

Limitation

Research results are given based solely on analysis of information from case studies in a developing country. Therefore, the results of this study can be used for other developing economies. Future studies can build on this study to expand on case studies in less developed, developed, or emerging economies to draw more comprehensive conclusions.

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Author Contributions

Chawalit Jeenanunta contributes to conceptualization, methodology, validation, analysis, investigation, data collection, manuscript editing, visualization, supervision, and funding acquisition. Le Thi Ngoc Lan contributes to conceptualization, methodology, validation, analysis, investigation, data collection, draft preparation, and manuscript editing. All authors have read and agreed with the manuscript before its submission and publication.

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References

Abhishek, Bhamoriya, V., Gupta, P., Kaushik, M., Kishore, A., Kumar, R., Sharma, A., and Verma, S. (2020). India's food system in the time of COVID-19. *Economic and Political Weekly* 55(15): 12-14. Retrieved from https://www.epw.in/journal.

Abdullah, F. M., Saleh, M., Al-Ahmari, A. M., and Anwar, S. (2022). The Impact of Industry 4.0 Technologies on Manufacturing Strategies: Proposition of Technology-Integrated Selection. *IEEE Access.* 10. 21574- 21583. doi: 10.1109/ACCESS.2022.3151898.

Alejandro, G.F., Lucas, S.D., and Néstor, F.A. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*. 210. doi: 10.1016/j.ijpe.2019.01.004.

Bartik, A. W., Bertrand, M., Cullen, Z. B., Glaeser, E. L., Luca, M., and Stanton, C. T. (2020). How are small businesses adjusting to COVID-19? Early evidence from a survey. *National Bureau of Economic Research*, 26989. Retrieved from http://www.nber.org/papers/w26989

Braun, V. and Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*. 3: 2, 77-101. doi: 10.1191/1478088706qp063oa

Chiaramonti D., and Maniatis K. (2020). Security of supply, strategic storage and COVID-9: Which lessons learnt for renewable and recycled carbon fuels, and their future role in decarbonizing transport? *Applied Energy*. 271. 115216. doi: 10.1016/j.apenergy.2020.115216

Choi, T.M. (2020). Innovative "Bring-Service-Near-Your-Home" operations under Corona-Virus (COVID-19/SARS-CoV-2) outbreak: Can logistics become the Messiah? *Transp. Res. Part E Logist. Transp. Rev*. 140, 101961. doi: 10.1016/j.tre.2020.101961

Chowdhury, P., Paul S.K., Kaisar S., and Moktadir M.A. (2021). COVID-19 pandemic related supply chain studies: A systematic review. *Transp Res E Logist Transp Rev. Apr*; 148:102271. doi: 10.1016/j.tre.2021.102271. Epub 2021 Feb 13. PMID: 33613082; PMCID: PMC7881707.

Dalenogare, L. S., Benitez, G. B., Ayala, N. F., and Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. *International Journal of Production Economics. doi:*10.1016/j.ijpe.2018.08.019

Dontoh, A., Radhakrishnan, S., Ronen, J. (2020). The Declining Value Relevance of Accounting Information and Non-Information-Based Trading: An Empirical Analysis. *Contemporary Accounting Research*. 21. doi: 10.2139/ssrn.230826.

Deaton, Angus S. (2021). COVID-19 and Global Income Inequality. National Bureau of Economic Research. No. w28392. Retrieved from https://ssrn.com/abstract=3772639

Derevyankina, E.S., Yankovskaya, D.G. (2020). The impact of COVID-19 on supply chain management and global economy development. *Int. J. Supply Chain Manag*. 9, 765–774

Dente, S.M.R. and Hashimoto, S., (2020). COVID-19: A pandemic with positive and negative outcomes on resource and waste flows and stocks. *Resour. Conserv. Recycl.* 161, 104979. doi: 10.1016/j.resconrec.2020.104979

Govindan, K., Mina, H., Alavi, B. (2020). A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19). *Transp. Res. Part E Logist. Transp. Rev.* 138, 101967. doi: 10.1016/j.tre.2020.101967

Gunessee, S., Subramanian, N. (2020). Ambiguity and its coping mechanisms in supply chains lessons from the COVID-19 pandemic and natural disasters. *Int. J. Oper. Prod. Manag.* ahead-of-print, 1– 23. doi: 10.1108/IJOPM-07-2019-0530

Gurbuz, I.B. and Ozkan, G. (2020). Transform or perish: preparing the business for a post-pandemic future. *IEEE Eng. Manag. Rev.* ahead-of-print, 1–6. doi: 10.1109/EMR.2020.3014693

Handfield, R.B., Graham, G., Burns, L. (2020). Coronavirus, tariffs, trade wars and supply chain evolutionary design. *Int. J. Oper. Prod. Manag*. ahead-of-print, 1–12. doi: 10.1108/IJOPM-03-2020-0171

Hakovirta, M., Denuwara, N. (2020). How COVID-19 redefines the concept of sustainability. *Sustainability* 12, 3727. doi: 10.3390/su12093727

Ivanov, D. (2020). Predicting the impacts of epidemic outbreaks on global supply chains: a simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transp. Res. Part E Logist. Transp. Rev.* 136, 101922. doi: 10.1016/j.tre.2020.101922

Iyengar, K., Bahl, S., Raju Vaishya, and Vaish, A. (2020). Challenges and solutions in meeting the urgent requirement of ventilators for COVID-19 patients. *Diabetes Metab. Syndr. Clin. Res. Rev*. 14, 499–501. doi: 10.1016/j.dsx.2020.04.048

Jabbour, A. B. L. de S, Jabbour CJC., Godinho Filho M., Roubaud (2018). Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. *Annals of Operations Research*. 270. doi: 10.1007/s10479-018-2772-8.

Koonin LM. (2020). Novel coronavirus disease (COVID-19) outbreak: Now is the time to refresh pandemic plans. *J Bus Contin Emer Plan.* 13(4):1-15. doi: 10.12691/ijcd-8-2-8

Le, T. AT, Vodden K., Wu J., and Atiwesh G. (2021). Policy Responses to the COVID-19 Pandemic in Vietnam. *International Journal of Environmental Research and Public Health*. 18(2):559. doi: 10.3390/ijerph18020559

Leite, H., Lindsay, C., and Kumar, M. (2020). COVID-19 outbreak: implications on healthcare operations. *TQM J.* ahead-of-print. doi: 10.1108/TQM-05-2020-0111

Mahmood, S. (2021). Instructional strategies for online teaching in COVID-19 pandemic. *Human Behavior and Emerging Technologies*, 3(1), 199-203. Doi: 10.1002/hbe2.218

Margherita, A., and Heikkilä, M. (2021). Business continuity in the COVID-19 emergency: A framework of actions undertaken by world-leading companies. *Business Horizons. doi:* 10.1016/j.bushor.2021.02.020.

Mehrolia, S., Alagarsamy, S., and Solaikutty, V. M. (2021). Customers response to online food delivery services during COVID-19 outbreak using binary logistic regression. *International Journal of Consumer Studies*, 45(3), 396-408. doi: 10.1111/ijcs.12630

Milne, R. J., Delcea, C., and Cotfas, L. A. (2021). Airplane boarding methods that reduce risk from COVID-19. *Safety Science*, 134, 105061. doi: 10.1016/j.ssci.2020.105061

Moktadir, M. A., Kumar, A., Ali, S. M., Paul, S. K., Sultana, R., and Rezaei, J. (2020). Critical success factors for a circular economy: Implications for business strategy and the environment. *Business strategy and the environment*, 29(8), 3611-3635. doi: 10.1002/bse.2600

Paul, S.K., and Chowdhury, P. (2020). A production recovery plan in manufacturing supply chains for a high-demand item during COVID-19. *Int. J. Phys. Distrib. Logist. Manag.* ahead-of-print, 1–22. doi: 10.1108/IJPDLM-04-2020-0127

Rowan, N.J., Laffey, J.G. (2020). Challenges and solutions for addressing the critical shortage of supply chain for personal and protective equipment (PPE) arising from Coronavirus disease (COVID-19) pandemic – Case study from the Republic of Ireland. *Sci. Total Environ*. 725, 138532 https://doi.org/10.1016/j.scitotenv.2020.138532.

Seetharaman, P. (2020). Business models shifts: Impact of COVID-19. *International Journal of Information Management.* doi: 10.1016/j.ijinfomgt.2020.102173.

Sahebjamnia, N., Torabi, S. A., and Mansouri, S. A. (2018). Building organizational resilience in the face of multiple disruptions. *International Journal of Production Economics*, 197, pp. 63-8. doi: 10.1016/j.ijpe.2017.12.009

Sharma, A., Adhikary, A., and Borah, S.B. (2020). COVID-19′s impact on supply chain decisions: strategic insights from NASDAQ 100 firms using Twitter data. *J. Bus. Res.* 117, 443–449. doi: 10.1016/j.jbusres.2020.05.035

Van Barneveld, K., Quinlan, M., Kriesler, P., Junor, A., Baum, F., Chowdhury, A., Junankar, P.N., Clibborn, S., Flanagan, F., Wright, C.F., Friel, S., Halevi, J., and Rainnie, A. (2020). The COVID-19 pandemic: Lessons on building more equal and sustainable societies. *Econ. Labour Relations Rev.* 31, 133–157. doi: 10.1177/1035304620927107

Van Hoek, R. (2020). Research opportunities for a more resilient post-COVID-19 supply chain – closing the gap between research findings and industry practice. *Int. J. Oper. Prod. Manag.* 40, 341–355. doi: 10.1108/IJOPM-03-2020-0165

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Appendix

Appendix 1

Table 3. Thematic analysis

Descriptive of the transcript		Company 1	Company 2	Company 3	Company 4
Theme	Code				
Effect of COVID – 19	Lack of employee	The company faces many difficulties due to many infected workers and the local government's measures to prevent the spread of the disease.	The company gave workers a complete break during the epidemic, and office staff and managers worked at home.	Most of the workers are infected and trapped due to the isolation, blockade, and local closure orders of the state.	The shortage of personnel is not much because the company applies many modern lines and advanced technology in production, operation, and management.

	Decreased order number	The company's customers and suppliers were similarly affected by the epidemic, so the number of orders fell by 25% compared to the expected volume of orders before the pandemic hit	During the first and second outbreaks in Vietnam, the company stopped production completely and filled existing orders with the inventory. The orders decreased sharply	The number of orders dropped sharply in the first 3 outbreaks. In the 4th phase of the epidemic, production activity improved again, but the order volume was still 25% lower than before the pandemic	The number of orders dropped sharply in the first 3 outbreaks due to the difficulties in logistics and import and export procedures
	Lack of materials	The shortage of raw materials was up to 50% due to the lockdown, which caused logistics and supply chain system disruption.	The company temporarily closed production during the first two phases of the pandemic. In the third phase, the company resumed production, but domestic materials were also in severe shortage. It is estimated that the available raw materials could only meet about 20% of the needs of the company.	Raw materials are mainly sourced domestically. There is still a severe shortage of raw materials due to the broken supply chain and the stagnation of the national logistics system. However, at the same time as the shortage of raw materials, the number of orders also decreased sharply, so the shortage of raw materials did not affect the fulfillment of orders much.	Raw materials are mainly imported from abroad, and customers are also abroad. Therefore, during the pandemic, the company faced many difficulties, from importing raw materials to delivering refined products to customers.
	Increase lead time	The bans on people going out, medical isolation, and closure of infected localities caused the company's logistics system to be delayed, leading to an increase in the lead time of up to 30% compared to the rate before the pandemic.	The company stopped production during the first 2 phases of the pandemic. Since the third phase of the Covid-19 epidemic, employees have returned to normal work. However, production time is still increasing due to the government's disease control activities.	The lead time increased by about 20% due to the prolonged logistics time.	The lead time was extended by at least 30% due to movement restrictions and more cumbersome export procedures.
	Increase operation cost	Increased costs: epidemic prevention, production maintenance	Operation costs do not increase much due to the closing of production activities.	Company expenses for supporting workers to work and eat at the factory, expenses related to medical products for checking and protecting workers' health, a sudden increase in logistics costs	Incurred many expenses to serve workers working and sleeping at the company according to the state's regulations. In addition, the cost of logistics and customs procedures increased during the epidemic period.

Industry 4.0 Readiness	Smart Factory	Digital Modeling: Does not exist Equipment infrastructure: The company uses remote management software. Meetings and discussions are conducted through the application of Zoom or Google Meet.	Digital Modeling: Does not exist Equipment infrastructure: The company uses data analysis and automated management software in accounting and customs.	Digital Modeling: Does not exist Equipment infrastructure: Enterprise Resource Planning (ERP), and	Digital Modeling: Does not exist Equipment infrastructure: Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES), IoT
	Smart Operations	Cloud usage: Does not exist Autonomous processes: Do not exist Information Sharing: Does not exist	Cloud usage: Does not exist Autonomous processes: Do not exist Information Sharing: Does not exist	Cloud usage: Exists Autonomous processes: The company uses some techniques in production, such as sensors, actuators, Programing Logic Controllers (PCL), Supervisory Control and Data Acquisition (SCADA), Information Sharing: Identification and traceability of raw materials/ products, Digital platform with suppliers/ customers/ other partners	Cloud usage: Exists Autonomous processes: The company uses some techniques in production, such as sensors, actuators, Programing Logic Controllers (PCL), Supervisory Control and Data Acquisition (SCADA), Information Sharing: Identification and traceability of raw materials/ products, Digital platform with suppliers/ customers/ other partners
	Strategy and organization	Divide the company into branches in many provinces, and set up funds for risk management. No need to change the production process	Prepare employees for a stable place to live and allocate annual risk management activities costs. Invest more in software to support production and remote management.	Prepare an annual risk funding budget. They are developing remote working tools. Prepare a human resource mobilization plan, prepare multi-skills for employees to rotate personnel	Business continuity plan. Prepare an annual risk funding budget. Closely connected supply chain Prepare a human resource mobilization plan, prepare multi-skills for employees to rotate personnel
	Employee	Employee skill sets for Industry 4.0: Operation personnel skills: are not capable; Manager capability: are not qualified	Employee skill sets for Industry 4.0: Operation personnel skills: are not capable; Manager capability: low capability	Employee skill sets for Industry 4.0: Operation personnel skills: basic capabilities; Manager capability: high capability.	Employee skill sets for Industry 4.0: Operation personnel skills: basic capabilities; Manager capability: high capability.
	Smart product	Does not have	Does not have	Does not have	Does not have
	Data-driven services	Does not have	Does not have	Has	Has
Leader's perceptio	Industry 4.0	Keep the current process	Learn and prepare for changing	Learn more about Industry 4.0 to get a higher level of readiness	Keep updating about new technology. Ready to invest more in Industry 4.0

	BCPs	Have no plan	Start planning for the future situation.	Continue working on BCPs	Continue to develop the current BCPs to adapt to future changes
Difficulties	System	The implementation cost of Industry 4.0.	The implementation cost of Industry 4.0. Lack of government support.	The implementation cost of Industry 4.0. Barriers between the company's physical infrastructure and the 4.0 technology system	The implementation cost of Industry 4.0

Appendix 2

Table 4. Cross-cases analysis

	Company 1	Company 2	Company 3	Company 4
Firm size	Medium	Medium	Large	Large
Firm type	Local	Local	Joint venture	International
Customer market	Local	International	Local	International
Supplier regions	Local	Local	Local and international	Local and International
Measures with COVID-19	Working from home, requiring workers to stay at the factory during the pandemic, regular measures required by the government	Stop working during pandemic	Reducing working hours, working from home, requiring workers to stay at the factory during the pandemic	Work as normal, requiring workers to stay at the factory during the pandemic, remote managing
Current productivity (after 2 years of the pandemic)	50% (From April 2021 to present)	20% (From April 2021 to present)	100% (From April 2021 to present)	80% (From April 2021 to present)
Business continuity plan	Does not have	Does not have	Had before a pandemic	Had before a pandemic
Industry 4.0 Readiness level	0 (Outsider level)	1 (Beginner level)	2 (Intermediate level)	3 (Experienced level)
Ready to change to adaptation	Not ready to change the current process	Ready to learn about Industry 4.0 technology. Preparation for staff skills	Ready to learn more about Industry 4.0 technology. Ready to update new suitable technology to their process. Invest in staff and management skills	Continuing to update new technologies