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Samanthi Weerabahu
Western Sydney University
Premaratne Samaranayake
Western Sydney University
Dilupa Nakandala
Western Sydney University

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W.M. Samanthi Kumari Weerabahu

School of Business, Western Sydney University,
Penrith NSW 2751, Australia

E-mail: S.Weerabahu@westernsydney.edu.au

Premaratne Samaranayake

School of Business, Western Sydney University,
Penrith NSW 2751, Australia

E-mail: p.samaranayake@westernsydney.edu.au

Dilupa Nakandala

School of Business, Western Sydney University,
Penrith NSW 2751, Australia

E-mail: D.Nakandala@westernsydney.edu.au

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Abstract

Industry 4.0 adoption is complex and challenging, making strategic guidelines vital for success in the digital transformation journey. While the positive aspects of I4 adoption in the manufacturing sector are reported in academic literature, evidence of I4 adoption in real-world situations from the triadic perspective of the supply chain is limited. Thus, this study aims to investigate the I4 adoption challenges and develop strategies to overcome those challenges, taking into consideration of triadic relationships in the supply chain. A qualitative research approach was adopted using interviews with supply chain practitioners. Lack of process/system integration, lack of competencies/skilled workforce, process-related issues, lack of conscious planning, and employees' resistance are identified as the key challenges of I4 adoption. Therefore, collaboration and partnership with supply chain actors to share resources/knowledge about I4 and implementing process excellence and digital learning are some strategies that manufacturing industries could use to overcome the challenges.

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1. Introduction

The fourth industrial revolution, referred to as Industry 4.0 (I4), provides tremendous opportunities and growth to businesses, supply chains, and various industry sectors. The industrial revolution unfolded through several phases (Xu et al., 2018). Industry 1.0 brought about steam power and mechanisation, while Industry 2.0 introduced mass production and electricity. In Industry 3.0, electronics, information technology, and automation are integrated into industrial processes, driving efficiency and productivity. These revolutions have shaped the modern world and paved the way for Industry 4.0, characterised by the fusion of physical and digital technologies like artificial intelligence, robotics, and the Internet of Things (IoT) (Yin et al., 2018, Xu et al., 2018). The increasingly popular Industry 4.0 still lacks a generally accepted definition (Culot et al., 2020). I4 is described as linking the digital or virtual world with the physical world through a large volume of data and advanced technologies (Bag et al., 2021). The applications of IoT, integration of cyber-physical systems in production and logistics operations, advanced human-machine interaction, and factory virtualisation are key elements of the I4 adoption (Stentoft et al., 2020, Lu, 2017).

The I4 adoption process is complex, and many organisations lack a clear roadmap or guidance for the I4 adoption (Roblek et al., 2016). Although the academic literature focuses on I4 readiness and maturity, evidence of I4 adoption in practice is limited (Bajic et al., 2020, Frank et al., 2019). Little attention has been paid to examining opportunities and challenges deemed relevant for adopting I4 concepts and technologies, and it is still unclear which opportunities and challenges are perceived as antecedents of I4 adoption in manufacturing companies (Müller et al., 2018). Furthermore, the existing literature about I4 adoption is restricted to pilot studies with limited effects on the entire firm and supply chains (Bajic et al., 2020). The challenges the manufacturing industry faces when adopting I4 seem to be even less investigated, considering the triadic perspective of the supply chain industry sectors and manufacturers' role as providers and users of I4 solutions (Müller et al., 2018, Ghadge et al., 2020). Thus, the current state of I4 adoption evidence is quite fragmented in discussion among practitioners and academics.

Thus, this study aims to investigate the I4 adoption challenges and strategies to overcome those challenges using a qualitative study of adoption experiences from the perspective of supply chain practitioners considering the triadic relationships in the supply chain. The rest of the article is organised as follows. First, the research background of I4 adoption in terms of

challenges of I4 adoption and strategies to overcome those challenges is presented. The research methodology, data collection via semi-structured interviews and analysis method are outlined next. This is followed by a discussion, theoretical and managerial implications of the research. Finally, the study concludes with a summary and limitations of the study. Further research is necessary to overcome the constraints on generalising the current findings since the limited scope of industry sectors hinders the consolidation of the phenomenon.

2. Research background

2.1. Industry 4.0 adoption

The I4 adoption process is complex, and the lack of a strategic roadmap or guidance may mean firms fail to evaluate their own capabilities and the benefits and outcomes of adopting I4.0 (Roblek et al., 2016). Sony and Naik (2019b) emphasise the need for new algorithms to manage supply chains in smart factories where structures change per customers' needs. Adopting I4 in supply chains will be more complex than a firm-level I4 assessment (Chauhan et al., 2021). These various readiness/ maturity assessment (Schumacher et al., 2016, Stentoft et al., 2020) models have their limitations and are not applicable to all scenarios, industries, and supply chains. Some maturity models offer few details about assessment methods and guidance to progress towards specific target levels. In supply chain analysis, both I4 readiness and maturity are important because different firms are at different maturity levels (Ghadge et al., 2020).

2.2. Challenges of Industry 4.0 adoption

The changes arising from the digital revolution in the production and value creation process are radical and pose a real challenge to organisations (Zhou et al., 2015). Many studies focus on the different types of challenges and barriers and have reported on technical challenges, including lack of infrastructure and internet-based networks (Chauhan et al., 2021); lack of standardisation and cybersecurity risk (Fereidouni et al., 2019); poor existing data quality and lack of integration of technology platforms (Luthra and Mangla, 2018). Moreover, strategic level and organisational challenges such as lack of government support and policy (Zhou et al., 2015), lack of digital culture; lack of financial resources; reluctance to change (Ageron et al., 2020); low management support and dedication (Zhou et al., 2015); lack of competency in adopting new business models and poor research and development on I4 adoption (Luthra and Mangla, 2018); talent management challenges (Whysall et al., 2019). Samaranayake et al. (2017) emphasised that integration and connectivity are the main challenges, as the integration

of systems within and across organisations requires a sustained high level of connectivity. Wankhede and Vinodh (2021) analysed 36 challenges of I4 technology adoption pertaining to the automotive sector using a case study and highlighted the linking/integrating physical production and digital factory in real-time as a key challenge.

It is perceptible from the previous studies that transitioning from the traditional manufacturing sector to the I4 setting is challenging and complex and requires strategic and operational planning at both firm and supply chain levels (Weerabahu et al., 2021). Therefore, it is important to optimise the framework conditions and support structures to meet the challenges and barriers of I4 and take advantage of the opportunities of the fourth industrial revolution.

2.3. Strategies for Industry 4.0 adoption

A review of management literature and practice uncovers that supply chain strategies, capabilities, and performance are increasingly important topics for practitioners and researchers equally (Müller, 2019). The transformation from traditional to digitally enabled manufacturing industries poses a real challenge to enterprises. Manufacturing companies need to develop strategies in good time to exploit the new possibilities of digitalisation, improve established processes and develop new business models (Ageron et al., 2020). Adopting I4 technologies and concepts is a complex process that requires long-term commitment and strategic insight (Sony and Naik, 2019a). Furthermore, Raj et al. (2019) argued that I4 adoption is a strategic decision, and organisations need to develop a digital strategy to implement I4 initiatives. Different approaches for adoption, including a methodology-based approach for SMEs (Ramírez-Durán et al., 2021) and a readiness assessment-based approach (Frank et al., 2019), have been proposed. The integration of lean concepts and I4 technologies has gained increased attention. Some recent studies include the adoption of I4 technologies in pre-medical diagnosis (Ilangakoon et al., 2021) and lean management as a critical success factor in I4 adoption (Pozzi et al., 2023). However, many studies stated that the manufacturing industry needs to focus more on clear digital strategies building through supply chain dynamic capabilities to gain a competitive advantage in the I4 era.

3. Research Methodology

This research adopted qualitative case inquiry on organisations representing a manufacturing industry due to the exploratory nature of the study. To investigate the I4 adoption phenomenon, an intensive, in-depth, and detailed investigation needs to be carried out, which could well be

supported by using a case study method (Yin, 2009). The main informants selected from the manufacturing organisation, first-tier suppliers, and customers were senior-level supply chain practitioners/managers or individuals holding an equivalent position (e.g., digital transformation consultant, systems manager). A focal manufacturing firm that matured in I4 technology usage was selected as the main case study organisation of this research. The selection of the focal manufacturing firm was based on the fact that they have deployed I4 technologies to streamline their business processes and plans to implement various I4 strategies in the future. The apparel industry's supply chain in Sri Lanka was selected for this phase since the apparel sector in Sri Lanka has shown significant progress/development in the digital transformation process. The interviewees' profiles are displayed in Table 1.

Table 1: Profile of the interview participants

Interviewer code	Supply chain representation	Job Role	Work Experience	Firm Size
Interviewee 1	Raw material Supplier	Deputy General Manager (DGM)	14 yrs.	Large
Interviewee 2	Apparel manufacturer	Manager	9 yrs.	Large
Interviewee 3	Apparel manufacturer	DGM	20 yrs.	Large
Interviewee 4	Apparel manufacturer	DGM	18 yrs.	Large
Interviewee 5	Apparel manufacturer	Manager	11 yrs.	Large
Interviewee 6	Customer/retailer	Manager	9 yrs.	Large
Interviewee 7	SC Consultant	Consultant/Professor	20+ yrs.	Large
Interviewee 8	Raw material Supplier	Assistant Manager	5+ yrs.	Large
Interviewee 9	Raw material Supplier	Manager	6 yrs.	Large
Interviewee 10	Customer/retailer	Senior Vice President	10 yrs.	Large

All the participants represented large organisations (>200 employees) under the ABS classification (ABS_ANZSIC, 2006) and with adequate knowledge about the technology and digital transformation in the manufacturing sector and had served over four years with their respective firms and had more than five years of experience in the manufacturing sector. The selected participants were approached via e-mail and invited to be voluntary participants in this phase of the study. One-on-one semi-structured interviews were conducted with the participants to gain rich insights into the core themes. The interviews continued for 45 minutes to 60 minutes, and all the interviews were audio recorded. After the transcription of the ten interviews, Nvivo software was used for thematic analysis (Creswell and Creswell, 2017). A data reduction process was performed to reduce and classify the text into systematic and simplified themes to develop meaningful outcomes and insights.

4. Research findings

The research findings are related to the I4 definition from practitioners' perspective, the challenges of I4 adoption, and their relevance to the I4 readiness/ maturity of the organisations. The challenges of I4 adoption are outlined under the four main categories: Technological, financial, inter-organisational, and intra-organisational.

The many scholars considering I4 today need to confront the lack of an agreed-upon definition, posing serious limitations to theory building and research comparability (Culot et al., 2020). As the technology landscape and understanding of I4 have evolved significantly and there are increasing sense of confusion around the scope and characteristics of the I4 phenomenon. Even though all ten supply chain experts had an understanding of I4, they were unable to provide a clear definition due to the ongoing confusion between I4 and similar concepts. According to Interviewee 7:

"...I4 is an umbrella term used universally for the advanced technologies integrated with supply chain operations...However, it will be challenging to say because supply chain operations integrated into cloud computing, then it is supply chain 4.0".

Further, the below statement of Interviewee 6 demonstrates the common element of the I4 definition:

"...the whole concept of I4 will transform the industry...; for me, Industry 4.0 is the digitalisation of processes, technologies, IoT and everything, how these digital concepts can transform this material flows of supply chains...".

In addition, according to the respondents, I4 technologies and their impacts influence the micro (individual firms) and macro-level (country). This is evident from the statements such as:

"...impact of Industry 4.0 varies at the firm level and supply chain level. Also, as a developing country, we are focusing on a country-level digital roadmap, where both product and service industries and agriculture used digital technologies and created superior supply chain...."- Interviewee 8.

According to Interviewee 3, "Industry 4.0 is the use of advancement in technology in every process, to optimise the benefits of it, to support internal and external customer". I4 was conveyed as a part of the broader ICT infrastructure by all the interview participants. Four

respondents stated that lean manufacturing, automation and digitalisation as key overlapping areas of the digital transformation process.

"...the key elements we are currently using are Lean manufacturing, Automation, and Digitalization. That digitalisation will support data becoming into one system so that you can analyse the whole group in one go...So we get process excellence applying lean manufacturing, on top of that Automation and Digitalization into that platform...". -Interviewee 4.

4.1. Challenges to I4 adoption in the manufacturing sector

Challenges to I4 adoption in the supply chain from an interview participants' perspective are shown in Figure 1 based on the coding frequencies. 13 main themes were generated to represent these challenges from the thematic analysis and are outlined under four categories (Figure 2).

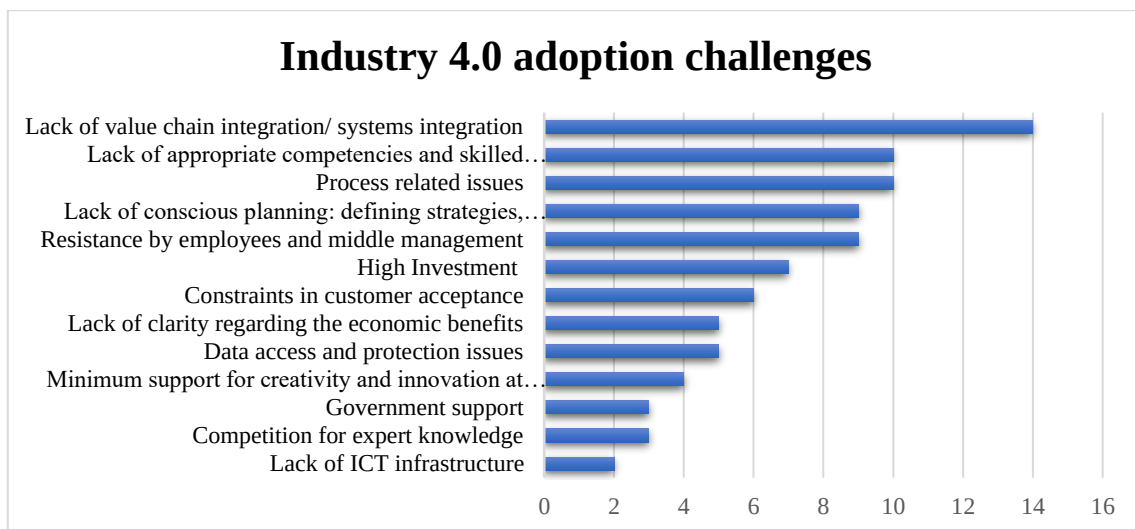


Figure 1: I4 adoption challenges

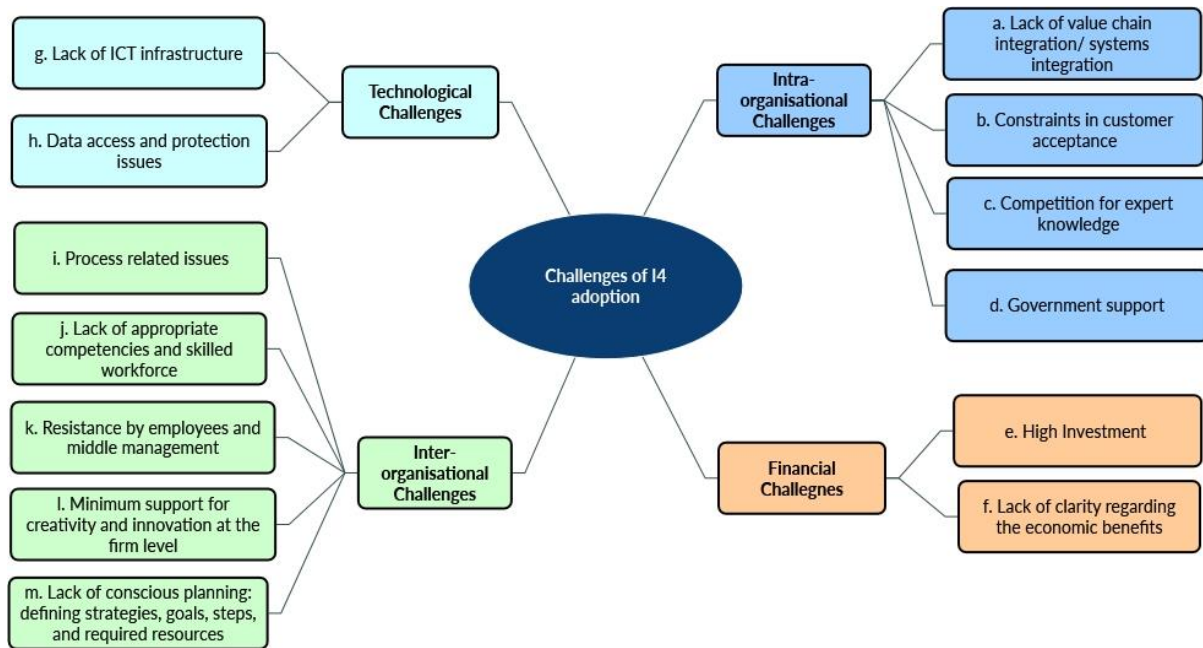


Figure 2: Four categories of I4 adoption challenges

4.2.1. Intra-organisational challenges

a. Lack of value chain integration/ systems integration

Many respondents discussed the lack of value chain integration/ system integration issues as a key challenge for I4 adoption.

The dispersed supply chain is one of the main reasons for the integration issues. As evident from the below statement: "... *the apparel manufacturing is a very dispersed supply chain. Most of the brands are in this part of the world in the USA, Vancouver, Canada and Europe. When it comes to the raw material manufacturing, the east part of the world like China to you know..., then production has moved into countries with low labour costs like India, Sri Lanka, Pakistan, Bangladesh to Africa....*"-Interviewee 6, this scattered manufacturing landscape brings certain challenges to I4 adoption.

In addition, many respondents emphasised system integration as a challenge for digital transformation. This is evident from the statements such as, "*One key challenge was system integration because the supplier would go with one system and big customer brands run in a different system, and we would run in a different system.*"-Interviewee 2

"The challenge is that integration, if a company has something like SAP, surely somebody using an industry 4.0 sensor gets a lot of information about the temperature, and they want to create

a digital twin. Oh, there's too much information SAP can learn. And as things evolve, we always develop new things, a new technology that can is very difficult to integrate..."- Interviewee 7

As explained above, focal manufacturing companies are using ERP systems and integration of ERP systems across the value chain to connect and synchronise to other I4 applications and data sources is challenging in the I4 setting.

b. Constraints in customer acceptance

Constraints in customer acceptance and flexibility of customer end to adopt I4 solution is another challenge for I4 adoption. During the interviews, some respondents stated they have very limited control over customers, and some customers are unwilling to pay additionally for the I4 embedded solutions.

"...If you talk about the apparel industry, the customers pay only the value-adding operations such as sewing and cutting. So other than that, the customer is not willing to pay. Because other than that entire process in the upscale process, whatever the activity we are performing..."- Interviewee 3

"So, there are certain things that we don't need; even unprecedented things would happen when it comes to standards...My honest experience is customers the big brands sometimes are a little reluctant to remove, specially the quality control process with an automated solution. They would still prefer to have some human to go and inspect it."-Interviewee 2

"...Again, that's our perspective because most of the time, manufacturers don't like to come to customers with ideas and suggestions and ask them to make changes. Instead, they would like to do whatever the customer asks them to do."-Interviewee 6

As explained above, specially manufacturing firms have little or no control over big brands/customers, and it is challenging to implement the supply chain-wide I4 adoption due to constraints in customer acceptance.

c. Competition for expert knowledge

I4 adoption requires a specific set of skills and knowledge; still, most organisations are at the initial level of the digital transformation process. Due to the limited number of expertise and high demand for I4 projects/movements, there is a competition for expert knowledge among competitive industries, as evident from the statement by Interviewee 4:

"We are finding it difficult to find people, so what you are looking at is maybe develop internally capable people, certify internal People. That also has a problem because if you develop people internally since there is no I4 education outside, those people are picked up and hunted by the other organisations...". Thus, competition for expert knowledge is a challenge for I4 adoption.

d. Government support

Government support in terms of funding, training and technical advice for the I4 adoption could expedite the digital transformation process. According to Interviewee 4, the Sri Lankan government supports the I4 transformation. However, the speed of government support is determined by the macro industries, and the government is behind the digital transformation timeline compared to other developed and developing countries. This could be challenging for the larger industries. This is evident by the statement:

"The challenge we are facing is the speed of the government is determined by the macro industry speed, but the speed that we want to go in maybe the government is on a speed like around us. Now they're trying to adapt, so we have gone far beyond that level. Apart from the tax benefits, they are making certain changes, but they are making those changes looking at the macro industry picture, so from their end, I don't think it is wrong, but for an organisation that has gone a little bit ahead from that is not getting the real benefit over the support from the government as needed." - Interviewee 4.

4.2.2. Financial challenges

e. High Investment

Most firms are still reluctant to invest in I4-related R&D, which poses challengingly high investment requirements (Raj et al., 2019). Thus, all the respondents indicated that it required increased investment regarding people, processes and technology at both firm and supply chain levels to be successful in the I4 adoption.

According to Interviewee 6, *"...I4 adoption helped us to enhance the competitive advantage, but again, the problem is these are a considerable investment, right doing that is not something easily or something cheap. So, these are very, and these are very costly initiatives..., low cost is one of the key requirements in my personal view even though we see those investments, as*

you know, not as an investment, but as a cost at the beginning, my personal belief and what I learned from those projects, in the long run, these technologies can reduce our costs..".

f. Lack of clarity regarding the economic benefits

Many industry practitioners have always questioned the economic benefits and productivity improvement of I4 Investment. One respondent came up with a global perspective on supply chains and stated that the big companies have several projects in their pipeline with less clarity about potential benefits. (as evident from statements such as: *"I see that in supply chain and my company, they have a lot of pet projects. And the typical one I mentioned is like blockchain for the supply chain. Many companies have surprised... [company Y] try, and a [Company x] try blockchain. And I was asking them, so did it work? And they say yes, it does work. So I asked them if they would scale them up, and they said No; why? What it does work, and it doesn't provide anything useful"- Interviewee 7).*

4.2.3. Technological challenges

g. Lack of ICT infrastructure

According to the respondents, many agreed that they must adapt and effectively use emerging ICT and their application as triggers for I4 adoption. However, as stated by the respondents, integrating I4 at the supply chain level requires integrating various hierarchical layers of the technology ecosystem with suppliers and customers. This is challenging as each supply chain partner is not at the same level of new ICT infrastructure. This is evident from the statements; *"When it comes to technology and ICT infrastructure, different entities are in different levels of the technology, infrastructure perspective. So that is, I would say, the biggest challenge we have right now because a full overview of the supply chain is missing..."*. - Interviewee 6.

h. Data access and protection issues

Many manufacturing organisations rely on data to run their operations and generate insights about customer needs and market dynamics. Due to the usage of a high volume of data, there are issues related to data access and protection. According to Interviewee 3:

"When we are working with supply chain partners, there are some concerns regarding data accessibility. ..So some of the things they still try to keep under their custody, their control is not fully open and sharing the information there. Specially in information sharing with customers".

Many respondents indicated that there are certain boundaries for information sharing and access. As evident from the statements, *"...basically I have some conversations and experience about how to share that real-time information, specially for market behaviour. With my suppliers, that is hard. Some secret areas like sample... if our supplier shares real-time information related to market behaviour then we can act faster"*- Interviewee 4.

Some respondents stated that they are concerned about protecting business information and precious knowledge about their systems against unauthorised access and theft. Thus, increasing data density with I4 brings challenges, particularly in cyber-security.

4.2.4. Inter-organisational challenges

i. Process related issues

With the low level of process capability, organisations continue to struggle to sustain in the competitive landscape and enhance performance with digital transformation. Furthermore, some respondents emphasised that some parts of the business process are still heavily dependent on manual labour. As stated by Interviewee 5,

"...in most of the big companies, even they use SAP and all, but the order follow up is happening in a manual manner..." and *"...in apparel manufacturing, you can't 100% eliminate the human involvement. Still 90% of our processes heavily depends on the manual labour"*.

Therefore, it is important to analyse the process and consider process improvement as part of the digital transformation process. As evident from the below statement:

"...we were fortunate to see the deviations and abnormalities because we were heavily working with lean manufacturing. In that case, I could see a lot of changes, a lot of abnormalities, a lot of waste, actually even the small part..., where the sewing operators do unnecessary work because of the complex supply chain operations, and we would be able to see those issues before I4 adoption..."- Interviewee 3, many respondents agreed that the prior work on process improvements using lean and six sigma projects largely influence the digital transformation.

Similarly, in manufacturing plants, due to the complex nature of the manufacturing operation and product variability, it is necessary to have human interaction.

"There are certain decisions that the human has to make. That has made the whole automation or robotics of this industry will be challenging, so the whole operation in the USA failed because they tried to do full automation, but it failed. The closest thing that came into was the

garment manufactured in the knitting machine itself. Other than that, the sewing and bonding part it's challenging." - Interviewee 4.

Furthermore, many respondents discussed the challenge related to standardisation. As evident from the statements:

"...there are various bar codes displayed on a pallet by the time we receive it in our warehouse; those are from different parties like suppliers, manufacturers, transport and warehouse. There is no standardised way to track from origin to use." - Interviewee 6.

As explained above, the complex nature of the processes within manufacturing operations, low level of process capability, and lack of standardisation are process-related challenges to the I4 adoption in the manufacturing sector.

j. Lack of appropriate competencies and skilled workforce

There is a desperate need to identify and develop the disciplines and the necessary abilities to build suitable skills into the workforce of Industry 4.0. Even though manufacturing is rapidly moving towards I4, there is still a lack of knowledge, skills and competencies of the workforce to suit the rapid digitalisation, as evident from statements of the respondents such as:

"The biggest challenge is to find people who are expertise in Industry 4.0 adoption and lean. Because you don't have any organisation that produces that expertise..." - Interviewee 4

Also, higher education institutions (e.g., universities and technical colleges) play a critical role in forming the social transitions requisite for I4 movements. However, today's higher education does not provide the necessary skills for shaping I4 adoption. As stated by Interviewee 4:

"We have certain degree programs, but what we find is it's really challenging to find the people who make the process standardised before you go to the automation and I4 adoption...So, I think the more crucial way to build the skills of I4 is by accurately adapting the learning factory concept. We have initiated this process by collaborating with Sri Lankan universities."

According to many respondents, two-way knowledge transfer channels and the synergy between industry and academia is important to foster the acquisition of the requisite skills for I4 adoption.

k. *Resistance by employees and middle management*

As many of the respondents stated during the interviews, employee and middle management resistance to the I4 initiatives is another crucial challenge. Due to the complex nature of some technologies and lack of knowledge/instruction about technology use, employees and middle management are not keen on digital transformation. As stated by Interviewee 5,

"Once, we were trying to introduce the tabs with certain systems in it. So, earlier, we saw resistance from people because some of the people and the team members level they haven't been exposed to such equipment. So, we have given to challenge that is to overcome that challenge...".

Moreover, change management is a challenge across the supply chain. As stated by Interviewee 5:

"We might do a trial, and we might see the results, and we are comfortable with using that technology. But our suppliers or customers may not have the same experience as us. Change management challenges are there...".

Due to the generation gap (workforce with older generation), organisations are getting into the problem of unskilled employees, as they are unaware of the I4 technologies and are unwilling to accept the changes embedded in the new business operations. The two respondents highlight this. As evident from the statement:

"...some of our manufacturing facilities operate with an older workforce, especially in the cutting department and shop floor. They are about 50 to 65 years old, and they are not willing to accept some changes in technologies."-Interviewee 3.

Some participants mentioned the resistance by employees is due to their fear of unemployment.

"Some of the shop floor level employees in our manufacturing plants are not satisfied with the new I4 initiatives top management suggested because they fear losing their jobs."- Interviewee 9.

As explained above, employee and middle management resistance is the key challenge for the I4 adoption.

l. Minimum support for creativity and innovation at the firm level

Many organisations promote innovation and creativity in their culture using various methods. However, still, organisations are facing the challenge of empowering employees and creating a supportive culture to promote innovation. For example, according to Interviewee 7, *"...So the challenge has been how do you empower people to do trials?"*.

Also, one interview participant stated that they lack a proper internal structure to promote innovation and an external structure to collaborate with supply chain partners to promote innovation within supply chain operations. As stated by Interviewee 9,

"We do not have a proper structure to do trial and error. I know people try the same things five times in different places. But there is no central place to coordinate the innovation...".

m. Lack of conscious planning: defining strategies, goals, steps, and required resources

The majority of the respondents stated that lack of planning, strategies and resources is the key challenge in I4 adoption. Multiple projects and dispersing strategic priorities are considered key challenges, as evident from the statements:

"... different strategic priorities, different knowledge levels, different technologies? Yeah, so these are the challenges. I don't think that is something we will ever be able to solve. I mean, creating equality in these areas, knowledge technology, in these areas, that won't work. So, I feel, to overcome this, what we need is the right strategy, I mean, the right strategy and cascading it down throughout the supply chain...". - Interviewee 6.

As explained above, the adoption of the I4 is a strategic decision. Even though there is a number of competing priorities, strategies and multiple projects toward digital transformation, top management, with the support of the bottom level, needs to develop a strategy, goal and steps by acquiring the resources to develop a digital strategy to implement the I4 initiative. Sometimes, organisations invest heavily in technology infrastructure without a clear strategy (*"Because they have invested heavily on that infrastructure without thinking about the agility and the ability to learn in the supply chain and future strategies... But when it comes to the front end of the business, I think this traceability is not only for the front end but for the entire value chain..."*- Interviewee 6).

5. Discussion, theoretical and managerial implications

This study explored the challenges and strategies of I4 adoption in the supply chain across the manufacturing sector. The findings indicated that suppliers, focal manufacturing companies, and customers face technological, financial, inter-organisational and intra-organisational challenges in the process of I4 adoption. Thematic analysis showed that, even though all ten supply chain experts had an understanding of I4, they were unable to provide a clear definition due to the ongoing confusion between Industry 4.0 and similar concepts (Culot et al., 2020). The thematic findings indicated that lack of value chain integration/system integration, lack of competencies and skilled workforce, process-related issues, lack of conscious planning and resistance by the employee and middle management were the key challenges of I4 adoption.

The findings of the earlier studies (Fereidouni et al., 2019, Luthra and Mangla, 2018, Ageron et al., 2020) suggested that value chain integration/system integration is the main challenge for I4 adoption. Therefore, the manufacturing sector can formulate the following strategies to overcome the challenges such as collaboration and partnership with supply chain actors to share resources /knowledge about I4, design or redesign agile manufacturing systems, and integrate manufacturing systems through base I4 technologies like cloud computing, react to rapid changes in the production process by adapting or developing technologies.

The study also found that a lack of competencies and a skilled workforce was the main challenge in the study context. The findings back up the previous scholarly arguments. For example, Raj *et al.* (2019) stated that companies have to assess their current skills and competencies and then define the future requirement of competencies. Adopting initiatives like learning factories for developing theoretical and practical knowledge in a real production environment and I4 (Baena et al., 2017), providing training, and creating multidisciplinary teams for I4 adoption are some viable strategies to overcome human resource challenges (Sony and Naik, 2019a).

Furthermore, these findings were in line with the findings of the prior manufacturing process and supply chain operation perspectives (Zhou et al., 2015, Chauhan et al., 2021), where streamlining the processes and improving the processes have an impact on supply chain performance. This study argued that process excellence and digital lean (Pozzi et al., 2023) could enhance the digitally enabled supply chain and eventually improves the supply chain performance. This study offered an understanding of and importance of digital strategy,

defining goals, steps, and required resources for I4 adoption. For example, organisations can focus on deploying I4 pilot projects with less investment in the beginning, develop/improve ICT infrastructure, and clearly outline the potential benefits of I4 adoption as key strategies.

The study contributes to a supply chain management and qualitative interdisciplinary probing body of knowledge that explores the challenges and strategies of I4 adoption across an array of supply chain processes centred across the manufacturing sector. While the literature is ornate with the challenges, barriers and drivers of I4 adoption, few studies so far investigated the ground reality of I4 adoption, considering the triadic relationship among supply chain actors. This study fills the knowledge gap at the intersection of supply chain and I4 adoption by establishing the fact that challenges of I4 adoption can be overcome by strategies such as collaboration and partnership with SC actors and digital lean and learning factories.

Practically, the research findings from the analysis of qualitative data on the adoption experience of the manufacturing sector supply chain actors provide noteworthy insights to practitioners in the supply chain and manufacturing sector with strategies to overcome the challenges of I4 adoption. Supply chain practitioners need to understand the potential benefits of I4 while deciding on any investment in supply chain operations. The thematic findings offered intuitions and intelligence that arise from the investment of I4, where industry practitioners, industry associations, and policymakers highly benefited.

6. Conclusion

The thematic findings indicate that lack of value chain integration/system integration, lack of competencies and skilled workforce, process-related issues, lack of conscious planning, and resistance by the employee and middle management are the key challenges of I4 adoption. The study suggests strategies such as collaboration and partnership with supply chain actors to share resources and knowledge about I4, design or redesign agile manufacturing systems and integrate manufacturing systems through base I4 technologies like cloud computing, adopting an initiative like learning factories, deployment of I4 pilot projects with less investment, in the beginning, develop/improve ICT infrastructure, process excellence and digital lean to overcome I4 adoption challenges. The findings of this semi-structured interview-based qualitative study of 10 supply chain practitioners provided a comprehensive understanding of I4 adoption challenges in the manufacturing-centred supply chain and strategies to overcome the I4 adoption challenges

There are some limitations to this study. Although ten cases are considered enough for consolidating a phenomenon, the current findings are limited by the scope of industry sectors. Therefore, the generalisation of the research findings is somewhat limited without further research in other contexts (e.g. broader spectrum of industry sectors). In future studies, various manufacturing sector organisation cases, including high-tech/low-tech, make-to-order/assemble-to-order/make-to-stock, can be used to get more evidence for generalisation. Also, the study explored the I4 adoption challenges considering the only triadic relationship of the supply chain. A survey study built on qualitative findings will be suitable to explore I4 adoption challenges and strategies from the evidence and experience of other firms in the supply chain.

7. Reference

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