Technological Forecasting & Social Change 175 (2022) 121394

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

The successful implementation of industry 4.0 in manufacturing: An analysis and prioritization of risks in Irish industry

Pezhman Ghadimi [a], Oisin Donnelly [a], Kubra Sar [a], Chao Wang [b,*], Amir Hossein Azadnia [c,**]

[a] Laboratory for Advanced Manufacturing Simulation and Robotics, School of Mechanical & Materials Engineering, University College Dublin, Belfield, Dublin 4, Ireland
[b] Research Base of Beijing Modern Manufacturing Development, College of Economics and Management, Beijing University of Technology, Beijing, China
[c] Department of Business Studies, Letterkenny Institute of Technology, Letterkenny, Ireland

ARTICLE INFO

Keywords:
Industry 4.0
Risk factor
Manufacturing
Best-worst method
Irish industry

ABSTRACT

Industry 4.0 is anticipated to revolutionize the manufacturing sector through a digital transformation. With this transformation, many benefits are expected, such as the automation and decentralization of production processes. Nevertheless, enterprises face considerable risks upon successful implementation of Industry 4.0. The uncertainties regarding these risks are currently hindering enterprises' implementation of Industry 4.0. Although several studies have investigated the adoption of Industry 4.0-related technologies, far too little attention has been devoted to identifying and analyzing the risk factors associated with the adoption of these technologies in manufacturing, especially in Irish industry. Therefore, this study contributes to the existing knowledge by proposing a systematic approach to identifying and ranking these risk factors along with recommending policies to mitigate the highest risks. Fourteen risk factors are identified, and the opinions of 12 industry experts across the Irish manufacturing sector are used to rank these risk factors using an adjusted best-worst method. The lack of standards and lack of methodological approaches was the highest-ranking risk factor, with the risk to capital investment, the lack of talent, the uncertainty in economic benefits and the potential delay to the manufacturing process ranking in the top 5. Policy recommendations to mitigate the highest-ranking risks are proposed based on an analysis of the Irish government's current Industry 4.0 policy. Governments should aim to assist industries in establishing comprehensive standards to increase the rate of successful Industry 4.0 implementation.

1. Introduction

Currently, the dawn of the fourth industrial revolution is just over the horizon (Cugno et al., 2021). With it, anticipation for the potential benefits it might bring is growing. Coined Industry 4.0, the fourth industrial revolution, is expected to have massive effects on the manufacturing industry and digitally transform current production processes. Hofmann and Rüsch (2017) described the advantages that Industry 4.0 could bring through the utilization of cyber-physical systems, including the Internet of Things and the Internet of Services. They highlighted how these systems used in conjunction could employ real-time data to make intelligent, adaptive, and predictive decisions in manufacturing processes. The successful implementation of Industry 4.0 is expected to create "smart factories" with a decentralized, flexible, self-organizing, and automated production environment (Büchi et al., 2020). It is also anticipated that Industry 4.0 will make mass customization possible, as Lasi et al. (2014) emphasized that the costs of producing goods are expected to fall while the volume of individually customized goods is expected to increase. It is clear that the implementation of Industry 4.0 will completely revolutionize current production processes and bring many benefits to the manufacturing industry.

Mirroring the industrial revolutions that came before it, the economic effect that Industry 4.0 is expected to have on the global manufacturing environment is vast (Culot et al., 2020). As Industry 4.0 can impact many different sectors, massive proportions of global economic output stand to benefit. Evans and Annunziata (2012) estimated that by 2025, Industry 4.0 could affect \$82 trillion of global output. Similarly, Manyika et al. (2013) projected that Industry 4.0 technologies will have a direct impact on tens of trillions of dollars of global economic output per year beginning in 2025. With Germany being the birthplace of Industry 4.0 and a superpower in mechanical and manufacturing

* Corresponding author.
** Corresponding author.
E-mail addresses: chaowanghn@vip.163.com (C. Wang), amir.azadnia@lyit.ie (A.H. Azadnia).

https://doi.org/10.1016/j.techfore.2021.121394
Received 30 March 2021; Received in revised form 29 October 2021; Accepted 23 November 2021
Available online 29 November 2021

engineering, it has emerged as the global center for Industry 4.0 innovation and research. For this reason, enterprises have begun strategically relocating to Germany to gain a competitive advantage, as highlighted by Hempel and Glemser (2017), who showed how many multinationals have flocked to Germany to research and innovate the best practices in implementing Industry 4.0.

For the Irish manufacturing sector to not be left behind, it is essential that the rate of implementation of Industry 4.0 in Ireland be increased. Evidence of this was given by the Irish government's Department of Business when it acknowledged how the manufacturing industry in Ireland is vulnerable to loss of competitiveness without firms' adoption of Industry 4.0 (Irish Department of Business, 2019). It is clear that Irish industries need to increase their rate of implementation to compete internationally. To give Irish enterprises the platform they need to implement Industry 4.0 technologies, research and development into the techniques, risks, challenges, and innovations involved will be required. Providing enterprises with additional information on Industry 4.0 implementation will offer a basis on which future manufacturing competitiveness and export-led economic growth can be secured for the Irish manufacturing sector.

The concept of Industry 4.0 is expected to bring a multitude of benefits for industrial value creation. However, the associated risks have hampered its implementation and lack a comprehensive overview. In response, this research aims to address these gaps by answering the following empirical research questions:

RQ1: What are the main risk factors faced by Irish industries upon the successful implementation of Industry 4.0 in Ireland?

RQ2: Which of these identified risk factors are the most important and will need to be prioritized?

RQ3: What could be done to mitigate these risk factors and promote the implementation of Industry 4.0 in Ireland?

This study aims to identify and rank the risk factors faced by industrial practitioners in the successful implementation of Industry 4.0. These risk factors are verified by industry experts so that they can be categorized and ranked in the order of their importance. The availability of a list of ranked risk factors may promote the increased adoption of Industry 4.0 in Irish manufacturing industries, laying the foundation for innovation and future sustainable economic growth. This study also aims to propose potential government policy and industry recommendations. These recommendations aim to mitigate the risk of the highest ranked risk factors, minimizing the potential loss due to risk factors faced during successful implementation. The research output should have significant practical implications for organizations, as it identifies the main risks and challenges of Industry 4.0 implementation. This will help firms in the process of Industry 4.0 strategy development, particularly in designing mitigation strategies for dominant risk factors.

The remainder of the paper is organized as follows: Section 2 provides a literature review, Section 3 discusses the research methodology, and Section 4 presents the results. Section 5 discusses the managerial implications. Finally, conclusions are provided in Section 6.

2. Literature review

2.1. Industry 4.0 and the Irish manufacturing sector

Many papers have proposed descriptions and definitions of Industry 4.0, but no exact definition has been agreed upon. Jacobi and Landherr (2013) offered one of the simplest descriptions, stating that Industry 4.0 "*will be an (r)evolution towards digitalization*". On the other hand, Hofmann and Rüsch (2017) proposed a more complete definition, describing Industry 4.0 as "*a shift in the manufacturing logic towards an increasingly decentralised, self-regulating approach of value creation, enabled by concepts and technologies such as CPS, IoT, IoS, cloud computing or additive manufacturing and smart factories, so as to help companies meet future production requirements*".

The Irish Department of Business (2019) highlighted how the Irish manufacturing sector was one of the pillars of the Irish economy and accounted for €140 billion in exports annually. The sector directly accounts for over 227,000 jobs while indirectly supporting 182,000 additional jobs. The sector mainly comprises the pharmaceuticals and chemicals, food and drinks, medical devices, computer and electronics, and engineering industries. Foreign-owned firms make up the mass majority (90%) of the gross value added in the manufacturing sector, while Irish-owned firms accounted for 50% of the direct employment in the manufacturing sector. Therefore, both foreign and domestic cohorts are vital to the manufacturing sector.

International benchmarking has signaled that Ireland is one of the frontrunners in terms of Industry 4.0 readiness, alongside Germany, Switzerland, and Sweden (Berger and Miller, 2015). Therefore, it should be expected that the Irish government will encourage and facilitate the adoption and implementation of Industry 4.0 processes and techniques for manufacturing firms operating in Ireland. To promote the adoption of Industry 4.0 and keep the manufacturing sector in Ireland globally competitive, the Irish government has produced Ireland's Industry 4.0 Strategy 2020–2025. The strategy describes a vision for Ireland's future manufacturing sector, goals the strategy hopes to achieve and strategic actions that will be taken to achieve these goals. The vision highlighted in the strategy is that "*by 2025 Ireland will be a competitive, innovation-driven manufacturing hub at the frontier of the fourth industrial revolution and the forefront of Industry 4.0 development and adoption*" (Irish Department of Business, 2019). The policy also defines five policy goals that describe the key outcomes of the strategy, which are listed below.

- To stimulate firms to adopt and build capability in Industry 4.0 technologies.
- To stimulate firms to harness the new opportunities enabled by Industry 4.0 technologies.
- To become a global leader in RD&I that underpins Industry 4.0.
- To facilitate the current and future workforce to develop the skills to deliver Industry 4.0 transformation and exploit the new opportunities arising in manufacturing and supply chain firms through Industry 4.0 technologies.
- To establish a world-class business environment for Industry 4.0 that is underpinned by an appropriate and internationally interconnected ecosystem of regulations, laws, and standards.

The Irish government's strategy for encouraging the implementation and adoption of Industry 4.0 is separated into six themes. Each theme focuses on tackling issues that fall under the headings of the themes. Strategic actions are the vehicles in which the issues identified in the strategy are addressed. The strategy put forward by the Department of Business has 18 strategic actions in total. It was highlighted that the implementation of Ireland's Industry 4.0 strategy has risks that have to be identified and managed. This forms the motivation of the next subsection, which focuses on defining various related risk factors identified through performing a comprehensive literature review. A brief description of these themes and their most important strategic actions is provided in Section 5, where the risk mitigation strategies are discussed.

2.2. Risk factors faced upon successful implementation of industry 4.0

For this study, the risk is considered "*A probability or threat of damage, injury, liability, loss, or any other negative occurrence that is caused by external or internal vulnerabilities, and that may be avoided through preemptive action*" (Dictionary, 2020). The literature review identified 14 risk factors that enterprises may face upon the successful implementation of Industry 4.0 manufacturing techniques. Table 1 illustrates the 14 identified risk factors. These factors are split into four categories, i.e., economic, social, technical, and external. In the following subsections, the definition of these identified risk factors is provided in detail.

Table 1
Identified risk factors.

Risk factor	Publications
Economic category	
Capital risk (CR)	Schröder (2016); Moktadir et al. (2018); Sanchez (2019)
Lack of clearly defined economic benefit (LDEB)	Koch et al. (2014); Kamble et al. (2018)
Potential delay to manufacturing during implementation (PDMI)	Wee et al. (2015); Alcácer and Cruz-Machado (2019)
Technical category	
Lack of standards and methodical approach (LS)	Koch et al. (2014); Xu et al. (2014); Hofmann and Rüsch (2017); Schröder (2016); Xu et al. (2018); Horváth and Szabó (2019)
Weak IT infrastructure & security issues (WIT)	Wee et al. (2015); Wee et al. (2016); Kamble et al. (2018); Stentoft et al. (2019)
Insufficient talent and technical knowledge (IT)	Koch et al. (2014); Wee et al. (2016); Tupa et al. (2017); Sanchez (2019); Whysall et al. (2019)
Uncertainty about the reliability of systems (URS)	Sung (2018); Orzes et al. (2018)
Poor data quality (PDQ)	Williams and Tang (2020); Luthra and Mangla (2018)
Social category	
Employee opposition (EO)	Kiel et al. (2017); Müller et al. (2020)
Bottlenecking (B)	Schröder (2016); Müller et al. (2018); Stentoft et al. (2019)
Uncertainty in the new business model (UBM)	Koch et al. (2014); Schröder (2016)
External category	
Lack of certification (LC)	Koch et al. (2014); Calia and D'Aprile (2020)
Legal issues (LI)	Koch et al. (2014); Schröder (2016); Kamble et al. (2018)
Change in economic climate or government policy (CEC/GP)	World Economic Forum (2018)

2.2.1. Poor data quality

Industry 4.0 consists of the use of complex systems that will generate high volumes of data from diverse sources. This means that companies will be interconnected at a much higher level than they were previously (Raj et al., 2020). This level of interconnection will, in turn, require an extensive infrastructure to store, process, and manage the data captured (Cordeiro et al., 2019). For the proper implementation of Industry 4.0, large volumes of real-time data will need to be collected and analyzed at high speed so that it will be possible for manufacturing processes to adapt to live changes in customer demand. Luthra and Mangla (2018) described the quality of data as one of the foremost requirements for successful decision-making systems in Industry 4.0. They highlighted how the generation and collection of big data are not possible without high-quality data. Similarly, Williams and Tang (2020) advocated that high-quality data are essential for the full transformation of manufacturing systems to Industry 4.0. They reported that poor data quality has a cascading effect within enterprises and that the compounding impact of poor data quality can negatively affect business decisions, efficiency, and credibility. There is a lack of standardization in data management, which is an additional challenge, as companies will have to acquire, use and interpret the information captured by the technology to generate value from the data (Cordeiro et al., 2019). Data competence must also be developed to ensure that value can be generated from the data. Birkel et al. (2019) argued that this is a particular challenge for small and medium-sized enterprises (SMEs), as they may not have as much access to experts in data handling. Relative to larger firms, SMEs may lack IT integration, as the subsequent software used is tailored predominantly toward larger organizations and is not toward resolving specific IT issues faced by SMEs (Mittal et al., 2018).

2.2.2. Lack of standards and methodical approach (LS)

Industry 4.0 will require communication and data sharing between many enterprises and their supply chains. Global and national standards will be required for communication between systems. Standards will also be required to ensure compatibility between systems. The importance of standards is illustrated in the literature. Xu et al. (2018) described that global standardization is essential to ensure the successful implementation of Industry 4.0. Similarly, Schröder (2016) showed how the lack of standards is a serious concern hindering the implementation of Industry 4.0. Standardization in data sharing systems is also required for secure, reliable data sharing between business partners. Hofmann and Rüsch (2017) commented on how the lack of standardization has negative impacts on enterprises that are trying to implement Industry 4.0. Horváth and Szabó (2019) also described how the lack of standardization is a major risk for enterprises looking to implement Industry 4.0. Due to this lack of global and general standards, it will make it more difficult for SMEs to join the value creation net. As a result of this challenge, firms may be reluctant to integrate Industry 4.0 technologies until defined standards and roadmaps are in place. This can make firms more susceptible to the risk of late investment, as competitors may already have the technology in place or key market trends may be missed.

2.2.3. Lack of certification

As Industry 4.0 differs for different manufacturing industries, there is currently no certification for proper Industry 4.0 implementation. Koch et al. (2014) found that the lack of certification is a major risk factor faced by enterprises looking to implement Industry 4.0. Calia and D'Aprile (2020) also highlighted that proper certification will be required for IT systems, data transfer and data security systems to reduce the risk faced by enterprises looking to implement new technologies. Enterprises looking to implement Industry 4.0 without the proper certification risk investing in vulnerable technologies that may be prohibited in the future.

2.2.4. Insufficient talent

To successfully implement Industry 4.0, experts with a high-level technical knowledge of the manufacturing process are required. Sanchez (2019) described how the successful implementation of Industry 4.0 would require special expertise in many technological areas. Training programs are crucial to developing employee skillsets, but Birkel et al. (2019) outlined the reluctance of employees to join these programs, which can lead to internal problems. The required skillset of workers is constantly changing, with importance placed on IT-related skills simultaneously with core business knowledge to create new, better-rounded employees. It is anticipated that a set of hybrid competencies will be required of emerging graduates, with a combination of ICT and business skills. External perspective employees with these skillsets can be hard to find on the market and usually seek high salaries, which makes it difficult for SMEs to compete with larger companies, which usually offer more attractive salaries and benefits. SMEs' lack of ability to access such external experts may lead to misinformed decisions based on a "gut feeling" of a manager or leadership team in an SME (Mittal et al., 2018). This may lead to a lack of confidence in decisions. For larger firms, decisions may be based on more concrete research and analysis. Moeuf et al. (2019)'s study indicates that it is evident that many companies are poorly prepared in terms of competences, especially in support functions and explains that SMEs usually do not have sufficient capital to send many employees to training programs for a significant period (Birkel et al., 2019). Therefore, SME employees are more likely to lack exposure to mentors, workshops, and supervised industrial training than those of larger firms. This can lead to a lack of employee participation in SMEs (Mittal et al., 2018).

2.2.5. Weak IT infrastructure and security issues

The introduction of Industry 4.0 technologies involves the adoption of highly integrated, complex systems. As a result, firms may become more sensitive and vulnerable to cybernetic attacks. Industry 4.0 requires that large amounts of data be available to many devices across the network. Luthra and Mangla (2018) outlined the importance of security to transform factories into smart factories, but the major vulnerability was found to be at the top of the supply chain. Tupa et al. (2017) explained that manufacturing and maintenance data from technical documents and specifications may become a goal for hackers. This would act as a major concern for companies, as through the use of Industry 4.0-based technologies, a variety of security issues may arise. The larger the network is, the more interfaces exist, which increases the potential areas of attack. Both SMEs and larger companies are susceptible to such attacks, and hackers may be more inclined to target larger companies. Raj et al. (2020) mentioned that firms are concerned about sharing their data with third-party software and service providers, which relates to the lack of data-sharing protocols, as companies are unaware of the severity of threats hackers pose through the implementation of more complex technology.

2.2.6. Capital risk

Installation of state-of-the-art IT systems and complex cyber-physical systems will be required for the full implementation of Industry 4.0. Significant amounts of capital will need to be invested by enterprises to commission these systems. Moktadir et al. (2018) highlighted how huge capital investments will be required to develop an Industry 4.0 infrastructure. SMEs may have tighter investment budgets than larger corporations due to their available capital and resources along with their predominant use of shorter-term strategies relative to larger firms. This can, in turn, make SMEs more susceptible to failed implementation. Moeuf et al. (2019) described the risk of obsolescence of investment in technology because by the time a firm has successfully implemented the chosen technology, another more efficient or superior technology may be available and in use by competitors. Moeuf et al. (2019) attempted to put this risk into perspective for SMEs by considering their agility and responsiveness to changes in the marketplace. In Birkel et al. (2019)'s risk framework, experts outlined the importance of considering the risk of false investments along with the time and manner of investments. The risk of late investments may arise if a company postpones investment, which may lead to companies missing key market trends as well as the opportunity to better position themselves on the market.

2.2.7. Lack of clearly defined economic benefit

Enterprises looking to implement Industry 4.0 are unsure of the economic benefit they will receive from their efforts. Luthra and Mangla (2018) explained that companies are likely to be reluctant to invest significant capital in digital technologies, as their economic benefit is unclear. This can create uncertainty for firms and increase the risk of investment when implementing these technologies due to insufficient information about their payback period. Most of these technologies are not yet at a mature stage, so clear financial definitions such as return on investment (ROI) are difficult to define. Therefore, financial departments will find it difficult to approve substantial investment until sufficient information is gained. There is a clear time lag between a company's investment and amortization that some firms may be wary of. Organizations may be reluctant to significantly invest due to this time lag, as lucrative benefits may come only after several years. Kamble et al. (2018) described the uncertainties in the cost benefits to be a major factor that affects Industry 4.0 implementation. They argued that there are nuances between different enterprises that make the calculation of exact benefits difficult.

2.2.8. Legal issues

Complex legal issues may arise during or after Industry 4.0 implementation. Schröder (2016) described how issues such as the handling of personal data, the protection of corporate data, the traceability of liability within a network and issues with international trade restrictions may arise due to Industry 4.0. Similarly, Koch et al. (2014) found that unclear legal situations were a major risk that enterprises faced with Industry 4.0 implementation. Kamble et al. (2018) highlighted that the employment of legal counsel may be required by enterprises to deploy a digital strategy. Legal issues arising as a result of Industry 4.0 practices act as a risk factor for enterprises.

2.2.9. Employee opposition

Implementation of Industry 4.0 would require a "*buy in*" from employees. Enterprises that are unable to communicate the benefits of Industry 4.0 to their employees may find themselves in a position in which implementation is opposed. Employee cooperation is critical to the successful introduction of these technologies. Industry 4.0 may create social tension in the labor market due to further division of the market into low-skills/low-pay and high-skills/high-pay categories (Raj et al., 2020). Birkel et al. (2019) reported that employees may question, delay, or obstruct the implementation of Industry 4.0. Their study found that fear of job losses, the lack of experience with new technologies, fears of unknown developments and fears of loss of competency may cause employees to reject the implementation of Industry 4.0 technologies. Similarly, Kiel et al. (2017) commented on how the disappearance of established job profiles due to automation may cause social problems. Without full employee buy-in, enterprises risk investing in Industry 4.0 systems without the workforce necessary to install or operate them.

2.2.10. Reliability of systems

Implementation of Industry 4.0 will require the installation of new cyber-physical systems and IoT networks. The reliability of these new networks and technologies will be unknown until they are tested as a full Industry 4.0 system. Sung (2018) highlighted how critical machine-to-machine communications currently lack reliability. Orzes et al. (2018) also described how enterprises are concerned about the uncertainty in the reliability of Industry 4.0 technologies, which prevents some enterprises from implementing them. Birkel et al. (2019) recommended that the systems must be as resilient and redundant as possible and a "fallback" solution in the event of a system failure must be introduced. Standards and expert advice will be critical to minimizing these risks, especially when considering the maturity of the adopted systems. This may create a reliance on experts for companies, but it would be viewed as more of a challenge for SMEs due to their difficulty in accessing such experts. There are also concerns surrounding the unpredictable nature of workers' reliability and their proximity to devices, which adds to the possibility of frequent health and safety issues (Badri et al., 2018). Ergonomics will have to come into consideration for companies to be fully confident that they have provided a safe working environment for employees.

2.2.11. Potential delay in manufacturing during implementation

Installation and commission of new equipment for Industry 4.0 adoption may take a significant amount of time, and it may also not be possible for enterprises to commission this equipment without interrupting manufacturing processes. Wee et al. (2015) described that many firms have reliable manufacturing systems and prefer incremental change as opposed to radical transformations. During the implementation phase of Industry 4.0 technologies, large changes occur for both equipment and processes. For companies, this may correspond to significant production delays or stoppage time. Factory-wide shutdowns with no production are seen as a last resort, as the effects are unknown when comparing the benefits and consequences. Alcácer and Cruz-Machado (2019) highlighted that the implementation of Industry 4.0 could add vulnerabilities to production processes that could then lead to production delays. Firms may be required to pause or reduce production during or after implementation. Enterprises that implement Industry 4.0 may risk the stoppage or delay of the current and future manufacturing process. Ivanov and Dolgui (2020) recommended the utilization of decision-making support to identify relevant scenarios, to monitor disruptions in real-time, and to determine the actions for the time of the disruption and subsequent recovery.

2.2.12. Change in economic climate or government policy

Unforeseen and unprecedented events such as Brexit and the COVID-19 pandemic will have a huge impact on both the economic climate and marketplace, but these effects are unknown and will only become fully evident as time passes. The Irish government's policies currently aim to encourage enterprises' implementation of Industry 4.0. World Economic Forum (2018) described how many governments globally are offering incentives to enterprises to invest in Industry 4.0 technologies and experiment through pilot schemes. This action by the government lowers the barriers to Industry 4.0 for enterprises, but funding cannot be guaranteed indefinitely. The coronavirus pandemic is expected to lead to the largest economic downturn in European history since World War II, which will include mass unemployment and waves of bankruptcy (Czifra and Molnár, 2020). The European Union (EU) economy is predicted to follow a V-shaped path with huge downturns for companies across all sectors and of all sizes. It is expected that there will be mass bankruptcies that governments will have to address strategically. The Irish government is currently expecting to spend up to €9 billion to deal with the effects of the COVID-19 pandemic in 2021 (Lehane, 2020). Czifra and Molnár (2020) outlined the importance of utilizing a flexible business approach, especially when considering unforeseen circumstances for companies to continue to be successful.

2.2.13. Uncertainty in the new business model

A new business model will be required to successfully take advantage of the benefits of Industry 4.0. Decentralization of the manufacturing process will require increased communication between divisions of an enterprise and may also interrupt established supply chains or logistics infrastructure. Many companies may lack expertise in developing data-driven business models, so subsequent guides and roadmaps are crucial to their successful implementation. According to Birkel et al. (2019)'s framework, SMEs are considered most at risk, as some describe that their current business models are not compatible with the deriving value from data and that larger companies would be at less of a risk due to their access to relevant experts. Schröder (2016) reported that the implementation of Industry 4.0 will require a great deal of restructuring of company organizations and that many companies lack comprehensive digital strategies. Enterprises that are currently trading profitably risk changing from a proven, successful business model to the selection and adoption of a new, untested business model.

2.2.14. Bottlenecking

Industry 4.0 requires full implementation along the supply chain. This means that for large companies or small local SMEs, all members of a firm's supply chain will need to be interconnected via Industry 4.0 networks. Early implementors may risk a lack of "*buy in*" from their business partners, reducing the efficiency and effectiveness of the system. Large companies may find it easier to secure funding for Industry 4.0 investments, while smaller firms may not be able to support this level of investment. Schröder (2016) highlighted how SMEs may take a "wait and see" approach toward implementation, allowing larger firms to set standards for technologies and business models. Stentoft et al. (2019) also described how many SMEs may not be able to secure the levels of funding required for implementation. As Industry 4.0 relies on all links in the supply chain sharing real-time information, large industry members conducting business with SMEs risk limiting the performance of the newly implemented manufacturing processes, as the smaller firms may not be able to support the large investment required to implement compatible Industry 4.0 systems. This will leave a gap in the communication along the supply chain that may reduce the overall effectiveness of Industry 4.0 methods.

The current research has two main contributions. First, we extracted and identified the full set of risk factors associated with the adoption of Industry 4.0 technologies in manufacturing, especially in Irish industry. Furthermore, a detailed explanation of each risk factor is provided to clarify the relevant risk factors associated with the adoption of Industry 4.0 technologies in manufacturing. Second, an adjusted BWM is proposed to rank the identified risk factors. The adjusted BWM solves the problem with finding the global weights of the alternatives associated with the traditional BWM. This ranking, followed by an extensive analysis and risk mitigation strategies, contributes to the theory and practice of Industry 4.0 application in manufacturing companies. The results of the study provide comprehensive insight to Irish government, policymakers, and industry practitioners regarding the existing risk factors and their mitigation strategies.

3. Research methodology

3.1. Selection of a suitable analytical approach

The objective of this study is to formulate a ranked list of risk factors that Irish industries may face upon the implementation of Industry 4.0 using suitable multicriteria decision modeling (MCDM) techniques. Therefore, this part of the research paper includes a literature review to help in the selection of the most suitable MCDM method for this decision problem. Then, a model can be created to prioritize the risk factors and provide insight into their importance. A comprehensive study on papers relating to risk analysis, prioritization, and assessment was completed to understand the suitable MCDM techniques. The papers examined were related predominantly to prioritizing the risks and challenges of various projects and concepts. Table 2 shows the relevant methods employed in the analyzed studies.

For the risk prioritization task, only one MCDM method is required to compute the weights of the risks, and then, their importance can be further analyzed from their weights. From the literature review, appropriate methods to compute the weights of the risks were defined as follows: the entropy, decision-making trial, and evaluation laboratory (DEMATEL); the analytic hierarchy process (AHP); and the best-worst method (BWM). These methods are further investigated to choose the most suitable technique. Among these techniques, the BWM is a relatively recent MCDM method; it differs from the AHP, as it requires a smaller number of comparisons (Khan et al., 2020). It employs a 1–9 scale to perform pairwise comparisons. This is beneficial because it requires less time to complete, so experts would be more likely to respond to the survey. It requires minimal input data, so the inputs are viewed as more reliable. It also only executes reference comparisons, which are seen as easier, more accurate, and less redundant than those in the AHP because secondary comparisons are not executed (Guo and Zhao, 2017). The consistency ratio of the BWM is high relative to other methods, such as AHP. Due to the advantages of the BWM, it was decided that it would be prudent to focus on this method. It was decided not to implement a fuzzy aspect of the model, as the experts' knowledge could be determined from the survey along with the calculation of individual consistency ratios.

Table 2
MCDM models in risk analysis.

Method	Publications
AHP and PROMETHEE	Prasanna Venkatesan and Kumanan (2012)
Fuzzy AHP, Fuzzy DEMATEL and Fuzzy TOPSIS	Sohrabinejad and Rahimi (2015)
Fuzzy AHP	Wang et al. (2012); Hariharan and Rajmohan (2019)
Fuzzy TOPSIS	Bakhtavar and Yousefi (2018)
ANP	Ilangkumaran et al. (2015)
Fuzzy Delphi and Fuzzy AHP	Turskis et al. (2019)
AHP and Fuzzy TOPSIS	Samvedi et al. (2013); Nazam et al. (2015)
BWM and Fuzzy TOPSIS	Norouzi and Ghayur Namin (2019)
BWM	Moktadir et al. (2018); Khan et al. (2020)

3.2. Proposed research methodology

In this subsection, a detailed explanation of the proposed research methodology and the implementation process are given. As the BWM was decided as the ranking method for the study, the formulation of a questionnaire to gather data using this ranking method was required. The BWM, developed by Rezaei (2015), requires 5 steps to be completed to provide a ranking of the decision criteria (risk factors in the current study). These five steps are described below.

- ***Step 1:*** *Determine a set of decision criteria.*

The decision criteria $C = \{c_1, c_2, ..., c_n\}$ are determined by the decision-maker (DM) and are equivalent to the risk factors identified and tabulated in Table 3 in this study. The most relevant risk factors were selected using a questionnaire. In this questionnaire, the experts were asked to provide a Yes or No answer to each of the listed risk factors based on their experience and opinion. A 50% threshold was applied to the data gathered using the questionnaire, meaning that if at least half of the respondents answered Yes to a risk factor, that risk factor was selected. The experts were also asked to modify the existing or add new risk factors that they thought were not included in the list based on their experience working in Irish manufacturing industry. After the first round of the survey, the questionnaire was reconstructed with any new/modified risk factors and recirculated. This approach ensured that the final list of risk factors provided in this research article captures Irish experts' opinions.

- - ***Step 2:*** *Determine the best and worst criteria.*

The DM is tasked with selecting the best and worst criteria from set *C,* given in step 1. The best and worst criteria are based on the DM's preference; the best criterion would be considered the most desirable or most important, while the worst criterion would be considered the least desirable or the least important. No comparisons between criteria are made at this stage.

- - ***Step 3:*** *Determine the preference for the best criterion over all the other criteria using a number between 1 and 9.*

The DM performs a pairwise comparison between the best criterion and all other criteria. The DM calibrates their preference for the best criterion over the others by using a number between 1 and 9. A value of 1 means that the best and other criteria are equally important, while 9 means that the best criterion is absolutely more important than the other. The meaning of the values that the decision-maker can choose from in the questionnaire are given in Table 3.

This will form the best-to-others (B2O) vector A_B,

$$A_B = (a_{B1}, a_{B2}, ..., a_{Bn}) \tag{1}$$

where a_{Bj} represents the preference of the best criterion over the other criterion.

Table 3
Intensity of importance for questionnaire selection.

Intensity of importance	Definition
1	Equal importance
2	Somewhat between Equal and Moderate importance
3	Moderately more important
4	Somewhat between Moderate and Strong importance
5	Strongly more important
6	Somewhat between Strong and Very strong importance
7	Very strong important
8	Somewhat between Very strong and Absolute importance
9	Absolutely more important

- - ***Step 4:*** *Determine the preference of the other criteria over the worst using a number between 1 and 9.*

The DM calibrates the preference for the other criteria over the worst criterion by using a number between 1 and 9. The value of 1 means the other criterion compared with the worst one is equally important, while 9 means the other criterion is absolutely more important than the worst. It is important to note that in both cases of the best-to-others and others-to-worst formulations, a favorable comparison is being made. Therefore, the selections given in Table 3 are used in both comparisons.

This will form the others-to-worst (O2W) vector,

$$A_w = (a_{1w}, a_{2w}, ..., a_{nw}) \tag{2}$$

where a_{jw} represents the preference of the other criterion over the worst.

- - ***Step 5:*** *Find the optimum weights of the criterion .*

In this study, the linearization method is used to find the optimum weight of the risk factors. The process used to linearize the BWM is as follows (Rezaei, 2016):

$$\begin{aligned} & \min max_j \{ |w_B - a_{Bj} w_j|, |w_j - a_{jw} w_w| \} \\ & \sum_j w_j = 1 \\ & w_j \geq 0, \text{for all} j \end{aligned} \tag{3}$$

The problem can then be programmed linearly

$$\min \xi^L$$

Such that

$$\begin{aligned} & |w_B - a_{Bj} w_j| \leq \xi^L, \text{for all} j \\ & |w_j - a_{jw} w_w| \leq \xi^L, \text{for all} j \\ & \sum_j w_j = 1 \\ & w_j \geq 0, \text{for all} j \end{aligned} \tag{4}$$

By solving the above problem, the optimal weights $(w_1^*, w_2^*, ..., w_n^*)$ and ξ^{L*} can be found.

To amalgamate the responses of a group of individual decision-makers, the arithmetic mean can be used. The mean w_{avg} is calculated using the following equation:

$$w_{avg}^* = \frac{1}{n} \sum_{j=1}^{n} w_j^* \tag{5}$$

The output from these linearizations will be the weights of the risk factors within their categories and the weights of the categories themselves. These weights are then combined by taking the arithmetic average, which gives the average weight of each risk factor and each category. These average weights can then be used to compute the average global weight of the risk factors. This is done by taking the product of the average weight of the risk factor and the average weight of the category it is contained in to give the average global weight of the risk factor. These global weights can then be used to compare the relative importance of the risk factors and give a final global ranking.

3.3. Adjusted global weighting approach

An issue was discovered with the ranking approach. To the authors' knowledge, this issue has not been systematically addressed in the current literature. The issue arises when global comparisons are to be made between criteria within groups of different sizes, with criteria in smaller groups being at an advantage to those in the larger groups. Because the issue stems from comparisons between criteria in groups of different sizes, it is not unique to the BWM and may be present in many ranking methods that involve global comparisons. A novel solution to this problem was derived, named the adjusted global weighting approach, which is described below. Take, for example, that there is a system in which 11 criteria need to be ranked. These 11 criteria are organized into 3 categories, given as SUP1, SUP2 and SUP3. If the decision-maker decides that all criteria are of equal importance within each group and all groups are also of equal importance, the weighting will be allocated, as shown in Fig. 1. It is obvious that in decision-makers' opinion, all factors should rank equally, and therefore, the global weights should all be equal.

If the traditional method given in Section 3.2 to formulate the global weights is used, subcriteria B1 and B2 will rank the highest, with both having a weighting of 0.165. The criteria from SUP3 all ranked the lowest, with all having an equal weighting of 0.066. Even though the decision-maker ranked all subcriteria and categories equally, the ranking formulated from the global weights shows a clear difference. It can be seen from this example that the issue arises when the criteria are split into categories unequally. As $\sum w_j = 1$, subcriteria within the smaller category will have an advantage over subcriteria that are in larger categories. This is a clear source of error in the current method of formulating a global weighting. Therefore, to solve this problem, an adjustment factor was used to adjust the subcriteria weights to make the comparison more reliable. The steps required to find the adjustment factor are given below.

Notation:

C_i: *i^{th} category,* $i = 1, 2, \ldots, m$

N_i: *Number of subcriteria in the i^{th} category*

$N_{\max}$: *Maximum number of subcriteria among all the categories*

W_i: *Weight of the i^{th} category*

W_{ij}: *Weight of the j^{th} subcriteria in the i^{th} category*

C_i^{AF}: *Adjustment factor of the i^{th} category*

W_{ij}^{Adj}: *Adjusted local weight of the i^{th} subcriteria in the j^{th} category*

W_{ij}^{G}: *Adjusted global weight of the i^{th} subcriteria in the j^{th} category*

First, the maximum number of subcriteria among all the categories (N_i) should be found. The subcriteria within the largest category are given an adjustment factor of 1. Thus, their weights remain unchanged. Then, to find the adjustment factor of all other smaller groups, the size ratio, given by the number of subcriteria of the smaller category to the largest category, is found. This ratio is the adjustment factor of the category. This can be calculated using Eq. (6):

$$C_i^{AF} = \frac{N_i}{N_{\max}}, i = 1, 2, \ldots, m \tag{6}$$

This adjustment factor is then applied to the weight of the subcriteria within this group by taking the product of the weight of subcriteria with the adjustment factor of the group. The local adjusted weight of the subcriteria can be calculated using Eq. (7):

$$W_{ij}^{Adj} = C_i^{AF} \times W_{ij}, \text{forall} i \text{and} j \tag{7}$$

The adjusted global weights of the subcriteria can then be calculated using Eq. (8):

$$W_{ij}^{G} = W_{ij}^{Adj} \times W_i \tag{8}$$

For the example given in Fig. 1, SUP3 was given an adjustment factor of 1, as it is the largest group with 5 subcriteria ($N_{\max}$). SUP1 and SUP2 were given adjustment factors of 4/5 and 2/5, respectively, using Eq. (6). Taking the adjustment factor into account using Eq. (7), the adjusted local weights of the subcriteria were calculated and are shown in Fig. 2.

As shown in Fig. 2, all subcriteria now have a weight of '0.2'. If the global weight is then calculated, it is clear that all criteria rank equally, as the decision-maker intended. It can be seen from this example that the inclusion of the adjustment factor gives a more accurate result; therefore, this method will be used in the calculation of the global rankings in the BWM linearization method. Table 4 gives the adjustment factors of the risk factors within the categories in the current study.

The results were validated by comparing them to the current literature. This process involved identifying correlations between the results from the empirical study and similar previous studies. Discussions were carried out on the results by identifying the top 5 ranking risk factors and analyzing them in-depth. The analysis involved assessing the effects the risk factors could have on enterprises and identifying the drivers behind these risk factors. Policy recommendations were proposed by analyzing the Irish government's current policy and identifying actions that could mitigate the effects of the highest-ranking risk factors. These actions were identified by consulting the current literature and the policies of international governments.

4. Implementation and results

This section describes the application of the research methodology (see Section 3) in the execution of the empirical study. A description of the steps involved in performing the study, as well as the results from the study including the expert responses, the resulting weights and analysis of these weights, are given in this section.

4.1. Questionnaire distribution and data collection

To form a ranking of the identified risk factors, the opinions of industry experts were required. For this study, industry experts were defined as "*any person who is working or has experience working in the manufacturing or supply chain industry in Ireland or any person who has conducted research on manufacturing and data analytics in Ireland with at least 5 years of experience*". Sampling took place in two ways: gathering contacts at the 2020 manufacturing and supply chain exhibition[1] and requesting the opinions of industry experts through the professional networking website LinkedIn. The manufacturing and supply chain exhibition attracts members of industry all over Ireland, and the exhibition provides a forum in which experts can share ideas, network, and obtain new business opportunities. Volunteers to complete the questionnaire were found by speaking to experts from various industries at the expo.

The questionnaire was hosted on Google Forms[2] and distributed through a hyperlink sent directly to industry experts. The hyperlink was distributed through email to contacts that were made at the 2020 manufacturing and supply chain expo. Additionally, by using LinkedIn, a hyperlink directing decision makers to the survey was posted in the target groups. This link allowed industry experts to fill in the questionnaire directly. Overall, 34 questionnaires were sent out directly to industry experts who were present at the expo, and the hyperlink for the questionnaire was also posted into 2 LinkedIn groups. Due to the nature of the study, some responses to the questionnaire were returned incomplete or inconsistently. Incomplete responses were removed from the dataset; overall, 3 of 18 responses were returned incomplete. Three responses were removed because they were considered inconsistent or randomly completed. Therefore, the empirical study had a total of 12 decision makers. Table 5 shows the experts' profile.

4.2. Weighting and ranking the risk factors

After gathering the data from the DMs, the BWM was utilized to weight and rank the risk factors. The BWM linear Excel solver was used to calculate the weights of the criteria. The model was run for 12 valid responses from the questionnaire, and the results were obtained. Table 6 gives the average weights of the risk factors, and Table 7 gives the average weights of the categories. These were found by taking the arithmetic average of the weights. Note how the adjustment factors, given in Table 4, are used here to adjust the values of the weights of the

[1] Further information on the 2020 expedition can be found at https://www.manufacturingevent.com/

[2] https://forms.gle/GZrLa3uMLQAmdZ1Y8

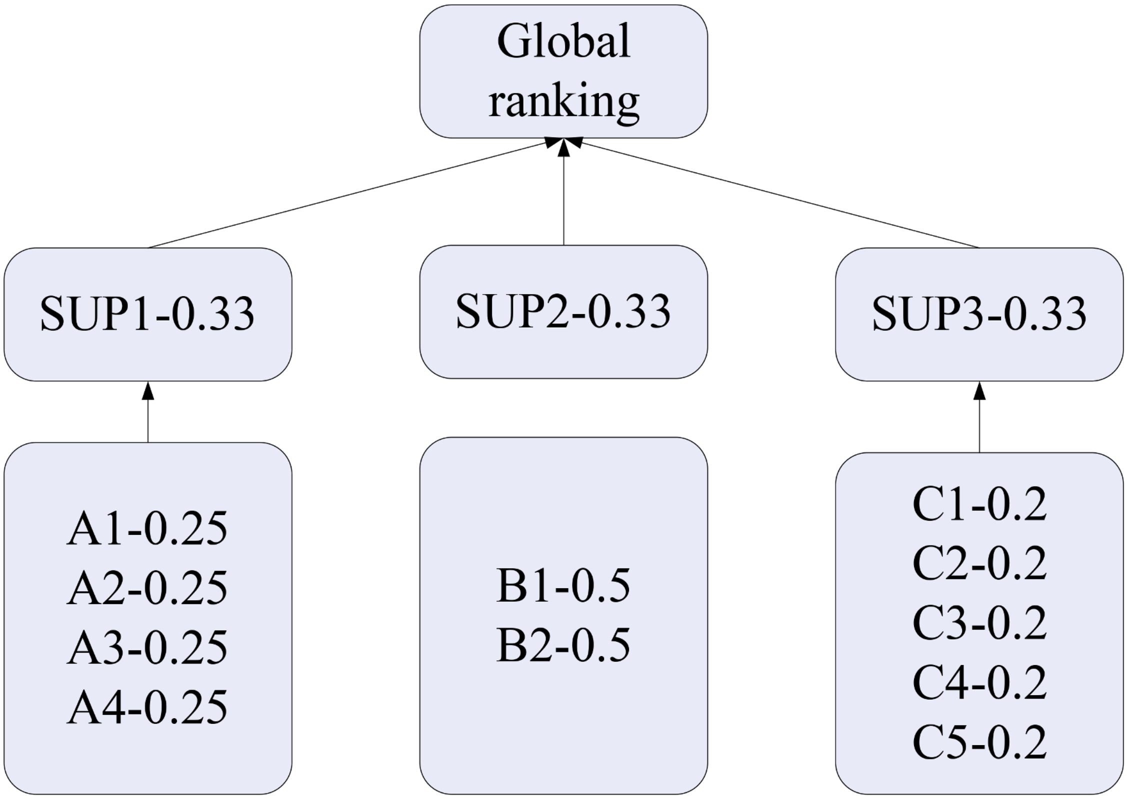

Fig. 1. Traditional weighting.

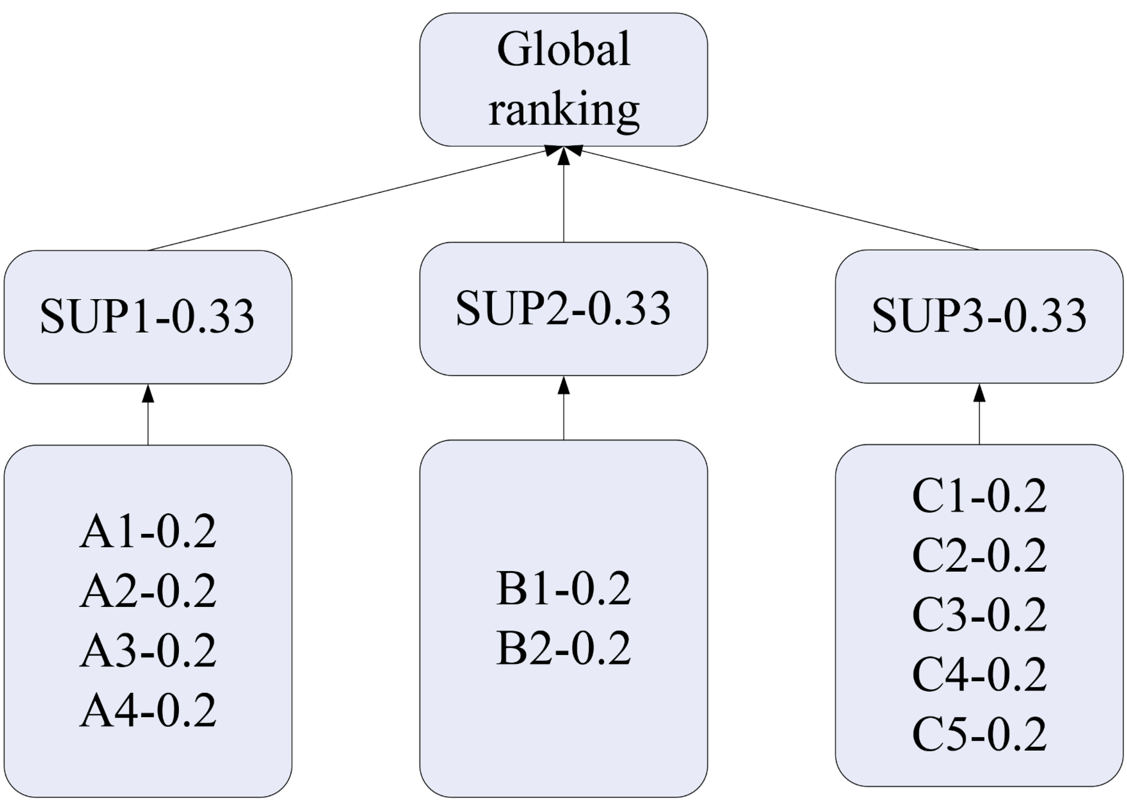

Fig. 2. Adjusted weighting.

Table 4
Adjustment factors.

Category	Economic	Social	Technical	External
Adjustment factor	0.6	0.6	1	0.6

Table 5
Experts' profile.

Type of experts	Work experience	
	5–10 years	*More than 10 years*
Academia	1	1
Professionals from industry	3	5
Industry consultants	–	2
Sum	4	8

Table 6
Average weights for the risk factors.

Risk Factor	CR	LDEB	PDMP	EO	B	UBM	LS
Local Weight	0.204405	0.200513	0.195082	0.139321	0.175708	0.28497	0.29549
Risk Factor	LT	WIT	URS	PDQ	GP/EC	LI	LC
Local Weight	0.224219	0.16887	0.176361	0.135061	0.266927	0.180025	0.153048

Table 7
Average weights for the categories.

Categories	Economic	Social	Technical	External
Local Weight	0.357137	0.172285	0.318779	0.151799

risk factors; therefore, the sum of the weights of the risk factors will not equal one.

Global weights were calculated using Eq. (8) for the 14 risk factors. These weights were formed by taking the product of the weights of the risk factors with the adjusted weight of the category they are associated with. Table 8 presents the 14 risk factors in order by weight according to the adjusted linear BWM.

5. Discussion

This section discusses the results from the empirical study. Individual mitigation strategies are required to minimize the impact of these associated risks for the successful implementation of Industry 4.0 technologies. Using these strategies, individual companies can further analyze these risks and various countermeasures. For this research paper, the strategic actions outlined in Ireland's Industry 4.0 Strategy are reviewed to assist in developing mitigation strategies for these defined risks. These strategic actions are categorized by the following relevant themes: Future Manufacturing Ireland (FMI), Awareness and Understanding of Concepts, Exploring and Planning, Implementation of Firm-level Industry 4.0 Strategies, Framework Conditions and Implementation of the National Industry 4.0 Strategy. Some of the key strategic actions to reduce the impact of these risks are presented in Table 9.

These strategic actions will now be discussed simultaneously with the related risk factors in accordance with the risk factors' positions in the final ranking. This approach will assist in further assessing the extent of these risks for Industry 4.0 implementation in Ireland. The discussion includes an in-depth analysis of the top 5 ranking risk factors and an analysis of the current Irish government policy that aims to mitigate these risk factors.

Table 8
Global ranks of the risk factors using the adjusted weighting method.

Rank	Category	Weight	Rank	Category	Weight
1	LS	0.094196	8	UBM	0.049096
2	CR	0.073001	9	PDQ	0.043054
3	LDEB	0.071611	10	GP/EC	0.040519
4	LT	0.071476	11	B	0.030272
5	PDMP	0.069671	12	LI	0.027327
6	URS	0.05622	13	EO	0.024003
7	WIT	0.053832	14	LC	0.023233

(1) ***Lack of standards and methodical approach***

The current absence of available standards and guides for Industry 4.0 technology implementation may cause a reluctance within companies to invest meaningful capital until such standards are developed. The lack of standards is a critical issue that enterprises face when implementing digital transformation to Industry 4.0. In Ireland's Industry 4.0 Strategy (Irish Department of Business, 2019), it is recognized that if companies take an active role in developing standards, competitive advantage can be gained. The National Standards Authority of Ireland (NSAI) has developed an Advanced Manufacturing Technologies Committee dedicated to standards in emerging technologies in manufacturing. The Irish government recognized this and set the "adoption and strategic use of relevant standards" as one of its visions for the future of manufacturing in Ireland. The government encourages interconnectedness between companies both nationally and internationally within the manufacturing sector so collaboration on standards development can occur.

The government within the defined strategic actions pledges to provide direct support to corporations to develop standards for process and for the implemented technologies. The main focus of these strategic actions is to provide support to enterprises so that their workforce can adopt the current standards, develop firm-level roadmaps toward Industry 4.0 standardization and engage in international Industry 4.0 standards fora. Calia and D'Aprile (2020) recommended that policymakers should look to support open source initiatives, organize workshops and conferences where standard-setters can meet and discuss paths forward. Calia and D'Aprile (2020) also highlighted how it will be important for policymakers to support licensing models that will allow various enterprises to adopt potential standards set by industry leaders. Due to the critical importance of these standards, it may be of benefit to the Irish government to set up a working group on standardization, similar to the German counterpart.

(2) ***Capital risk***

It was seen from the empirical study that many enterprises, especially smaller firms, considered financial risk when investing in Industry 4.0 to be a substantial factor in the decision-making process. The Irish government supports enterprises financially through strategic actions. These actions involve the allocation of state funding through direct RD&I grants as well as low interest fixed-term loans. These actions aim to incentivize enterprises to increase their investment in Industry 4.0 technologies and systems. To further help incentivize investment, the Irish government can look to reduce the potential tax obligations of firms that complete investments past a certain threshold. To reduce the risk faced by smaller firms, the government could also promote

Table 9
Key strategic actions to reduce risks throughout Industry 4.0 implementation as set out in Ireland's industry 4.0 strategy document (Irish Department of Business, 2019).

Theme	Strategic action
Theme 1: Future Manufacturing Ireland (FMI)	• Initiate a new coordination mechanism, FMI, to ensure coherent and effective delivery of RD&I supports across centers with a dedicated focus on Industry 4.0 technologies.
Theme 2: Awareness and Understanding of Concepts	• Raise understanding amongst manufacturing firms of the concept of Industry 4.0 and the potential benefits derived from adopting Industry 4.0 technologies. • Support the introduction of enterprise-led Industry 4.0 clusters. • Provide communication and guidance to firms throughout their Industry 4.0 journey, mapping where current digital capability and technical expertise may be found, and signposting public supports available.
Theme 3: Exploring and Planning	• Provide access to firms to Industry 4.0 demonstrators to allow them to experiment with individual Industry 4.0 platform technologies and gain further insight into these technologies. • Provide support to firms to develop Industry 4.0 pilots in-house that would act as exemplars to other firms. • Provide access to external expertise to support firms.
Theme 4: Implementation of firm-level Industry 4.0 Strategies	• Utilize current state programs to support firms to invest in Industry 4.0 technologies. • Investigate options for the establishment of an accelerated capital allowance scheme to encourage firm investment. • Support the development of strategic leadership and management skills in Industry 4.0. Provide support to firms to upskill their current employees. • Assess the skill requirements for Industry 4.0 and signpost to appropriate provisions.
Theme 5: Framework Conditions	• Provide support for SMEs through existing funding allocations to engage with at international Industry 4.0 standards fora. • Develop a plan for Ireland to enhance engagement in international activities and RD&I collaborative initiatives around Industry 4.0.
Theme 6: Implementation of National Industry 4.0 Strategy	• Establish an Industry 4.0 Stakeholder Forum to oversee implementation of the strategy.

investment by placing a guarantee on loans in the event of a failed implementation. The Future Growth Loan Scheme[3] creates support for longer-term credit to firms. This scheme can be utilized for both physical and intangible assets and other costs. The government has also pledged to investigate the effectiveness of an accelerated capital allowance scheme for firms. This would allow for the cost of equipment and intangible assets to be deducted at a faster rate than the standard capital allowances tax structure, which would increase firms' cash flow. These options can incentivize companies to implement these technologies while decreasing the concern surrounding payback periods and ROIs.

(3) ***Lack of clearly defined economic benefit***

Industry experts considered the lack of a clearly defined economic benefit as an important risk factor in Industry 4.0 transformation. The Irish government defined strategic action as estimating the economic benefit that firms may receive after successful implementation. This is done through the provision of external experts that can analyze the potential cost of the transformation and the eventual return on investment. This measure seeks to provide enterprises with insight into the potential profits they may receive as a result of implementing Industry 4.0 and reduce the levels of uncertainty. Further measures that the Irish government can take in this area include providing tax incentives or subsidies on profits to safeguard a minimum return on potential investments. This initiative can help incentivize enterprises to initiate Industry 4.0 implementation, as they are ensured a minimum return from their efforts. Increasing government spending on RD&I can also help to reduce the levels of uncertainty surrounding the potential economic benefit in the Irish manufacturing sector.

(4) ***Insufficient talent***

Industry 4.0 puts pressure on the current supply of available talent. Going forward, it will be crucial that the supply of talent does not hinder enterprise attempts at implementation. This is especially true for SMEs, as these enterprises are already at a disadvantage by not having the same resources to compete for talent as large firms. Based on Ireland's strategic plan for the future of manufacturing, the government has focused on skills development. Some strategic actions look at developing the management skills and strategic leadership required to deal with the transition to digital manufacturing and upskilling workforces to support the adoption of Industry 4.0 technologies and systems. This will help meet the immediate need for staff within industry. Assessment of the skills and job profiles required for employees transitioning into differing roles is required to further understand the extent of the shift in necessary skillset of employees. Employee skillset transformation may be required across differing departments, which further highlights the importance of the assessment phase. Existing employees require support and guidance to transition into new roles along with the adoption of a new skillset. The policy "Supporting Working Lives and Enterprise Growth in Ireland[4]" recognizes the challenges that are posed to firms by this lack of expertise and attempts to minimize this challenge. The government has pledged to provide targeted support for both employees and employers within the Irish labor market to overcome this challenge through both employer-based and state initiatives. An example of such support available to companies is the "Explore" program,[5] which focuses on lifelong learning to upskill employees in manufacturing and will thus allow employees to develop skills that are complementary to technological change.

Managers are initially challenged to understand any missing capabilities within the organization that may hinder the implementation process. Assessment of the skills and job profile required for employees transitioning into different roles is required to further understand the extent of the shift in the necessary skillset of employees. Employee skillset transformation may be required across different departments, which further illustrates the importance of the assessment phase. Existing employees require support and guidance to transition into new roles along with an adoption of a new skillset.

(5) ***Potential delay to manufacturing during implementation***

Industry experts believe that implementing Industry 4.0 may put their current production process at risk of delay or stoppage. The Irish government aims to mitigate this issue through strategic planning that will try to prevent any unforeseen impacts of implementation. Some strategic actions by the government aim to provide enterprises with demonstrators and access to in-house pilots to try to identify any potential issues before they can jeopardize production. Enterprises that are

[3] https://sbci.gov.ie/products/future-growth-loan-scheme

[4] https://www.solas.ie/f/70398/x/6bcb2aa9ff/supportingworkinglives_enterprisegrowth_policyframework_sept2018.pdf

[5] https://www.regionalskills.ie/regions/mideast/news-updates/explore-programme/

concerned about delays in their manufacturing processes during implementation can look at collaborating with other firms in their industry to ensure continued production. Collaboration between firms may allow them additional redundancy to ensure the production of their product in the case of a potential issue during implementation. This collaboration may allow for mutual safeguarding of production between competitors. Gradual transitory phases may be utilized to approach interruptions with caution. Incremental changes may add further success in the long term, as productivity may be maintained. Sufficient development of comprehensive plans to overcome interruptions to production will cause this risk to have little to no impact on the implementation phase.

5.1. Effect of adjusted global weighting approach

This section presents the results of a comparison to show the effect of the adjusted method. In this study, before the adjustment was applied, criteria from the economic group of risk factors ranked considerably higher than criteria from the technical group. After the adjustment, the technical criteria were fairly weighted, which allowed them to rank higher. This adjustment allowed the 'lack of standards' and 'lack of methodological approach' to be promoted to the most important risk factors, ranking higher than the 'potential delay to the manufacturing process' and the 'risk to capital investment'. Table 10 presents the comparison between the two approaches. It can be observed that the error from the group sizes has a significant impact on the results. In addition to occurring in the best-worst method, this error has the potential to arise in other MCDM methods, such as analytical hierarchy process (AHP) and extensions of AHP. Future work will be required to propose efficient heuristics to address this issue. Overall, the adjustment factor used to adjust the global weights of the criteria was shown to provide more reliable results, rectifying the error caused by the difference in group sizes.

5.2. Validation

This section describes the validation of the obtained ranking by the same experts. The first five top-ranked risk factors were presented to the 12 experts. Using an independent survey, each expert was asked to rank these five top-ranked risk factors again, from 1 to 5. Table 11 tabulates the results of this survey. Then, for each risk factor, the 1–5 rankings for all experts were summed for each risk factor. Table 12 shows the result of this further analysis. For example, 8 out of 12 experts assigned the LS risk factor a rank of 1, 3 experts a rank of 2, and 1 expert a rank of 3, and none of them assigned this factor a rank of 4–5. Subsequently, the results of this analysis were compared with the ranking obtained using the proposed analytical approach. If more than 50% of the experts (6 + 1) assigned the risk factor a rank similar to that achieved through the proposed approach, then the rank was accepted and validated. For instance, LS received a value of 1 (highest rank) from 8 experts (67% of the experts). Since more than 50% of the experts assigned this factor a value of 1, it was ranked as highest-ranking risk factor. This factor was also ranked highest using the proposed analytical approach (see Table 8). Using the same procedure, all five top-ranked risk factors were validated, as each of them obtained identical rankings from at least 7 experts using this validation approach.

Table 10
Comparison between adjusted and traditional BWM.

Risk factor	Weight, traditional	Rank, traditional	Rank, adjusted method
CR	0.1216	1	2
LDEB	0.1193	2	3
PDMP	0.1161	3	5
LS	0.0941	4	1
UBM	0.0818	5	8
LT	0.0714	6	4
GP/EC	0.0675	7	10
URS	0.0562	8	6
WIT	0.0538	9	7
B	0.0504	10	11
LI	0.0455	11	12
PDQ	0.0430	12	9
EO	0.0400	13	13
LC	0.0387	14	14

Table 11
Experts' rankings of the risk factors.

	Experts											
Risk Factors	1	2	3	4	5	6	7	8	9	10	11	12
LS	1	1	2	1	1	2	1	3	1	1	1	2
CR	3	2	1	2	2	1	2	2	2	2	3	1
LDEB	2	3	4	3	3	3	3	1	3	3	2	3
LT	4	4	3	4	4	5	4	4	5	4	6	4
PDMP	6	5	5	5	5	6	5	5	4	5	4	5

6. Conclusion and future works

The objective of this study is to identify the risk factors that Irish industries may face upon the successful implementation of Industry 4.0 and rank these risks in terms of their relative importance. This objective is carried out using an empirical study that focused on gaining the opinion of industry experts. The empirical study finds that the lack of standards and lack of a methodological approach were the most important risk factors in the opinion of industry experts. This result mirrors the current literature, as multiple extant papers reference that the lack of standards is a major reason why enterprises are not implementing Industry 4.0 even though it provides considerable benefits. For the idea of a digital manufacturing revolution to transpire, there will need to be significant efforts from global government and industry members to collaborate and work toward international standards. The Irish government should focus on aiding industries in developing comprehensive standards so that the rate of implementation of Industry 4.0 can increase.

The potential delay to the manufacturing process was one issue that industry experts would consider important but did not appear too frequently in the literature. In some manufacturing processes, downtime must be avoided at all costs. Therefore, the risk of implementing untested systems is too great, which shows how in industry, newer is not always better. It also highlights the disconnect between academics studying cutting edge technology and industry members who are then tasked to implement it. Reliability is a major factor in the value of technologies to manufacturing processes. Thus, ensuring that new Industry 4.0 technologies are reliable is imperative to their implementation.

One of the findings in this research work, which was not initially anticipated, was the presence of an error due to group size in ranking methods that involve a global ranking, such as the BWM or AHP. This error has the potential to disrupt a significant portion of the findings in the current literature. A novel approach to removing this error was formulated and used to increase the accuracy of the results in this study. A comparison was carried out between the traditional and adjusted methods to find the global weights of the risks.

Although the BWM has several advantages over some of the well-known MCDM approaches such as AHP, there are some limitations with the technique, as with every other MCDM method. As discussed in the manuscript, the robustness of the BWM suffers from its calculation of global weights of subcriteria when, in fact, the decision should be made between subcriteria within groups of different sizes. In this case, subcriteria in smaller groups are advantaged over those in the larger groups. In this study, to solve this problem, we proposed an adjusted BWM. In addition, the BWM suffers from complicated calculations when the number of alternatives in the decision-making problem is high. This

Table 12
Results of the validation process.

Risk factors	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank, proposed approach	Validated?
LS	8	3	1	0	0	1	√
CR	3	7	2	0	0	2	√
LDEB	1	2	8	1	0	3	√
LT	0	0	1	8	2	4	√
PDMP	0	0	0	2	8	5	√

problem is almost identical to that encountered in the other well-known MCDM techniques.

Key issues such as the lack of a system of standards, a large capital investment, a potential delay to the manufacturing process, a lack of appropriate talent and uncertainties about economic benefits hinder the implementation of Industry 4.0. It is crucial that the Irish government mitigate the effects of these risk factors so that the Irish manufacturing industry can remain competitive. Future work focusing on successful case studies will help encourage enterprises to begin the implementation of Industry 4.0. The proposed risk factors and rankings in this study can be used to develop a risk assessment framework and can be utilized in further case studies. Future work on the modified adjustment factor should be carried out to identify other ranking methods that may be vulnerable to this error.

CRediT authorship contribution statement

Pezhman Ghadimi: Conceptualization, Methodology, Data curation, Writing – original draft. **Oisin Donnelly:** Conceptualization, Methodology. **Kubra Sar:** Writing – review & editing. **Chao Wang:** Conceptualization, Writing – review & editing. **Amir Hossein Azadnia:** Methodology, Writing – review & editing.

CRediT authorship contribution statement

Pezhman Ghadimi: Conceptualization, Methodology, Data curation, Writing – original draft, Supervision. **Oisin Donnelly:** Methodology, Data curation. **Kubra Sar:** Writing – review & editing. **Chao Wang:** Conceptualization, Writing – review & editing. **Amir Hossein Azadnia:** Methodology, Writing – review & editing.

Acknowledgments

Financial support was provided in part by the National Natural Science Foundation of China (72071006 and 62073007) and Republic of Turkey Ministry of National Education (ZYPN5T3990HWQ7Z)

References

Alcácer, V., Cruz-Machado, V., 2019. Scanning the industry 4.0: a literature review on technologies for manufacturing systems. Eng. Sci. Technol., Int. J. 22 (3), 899–919.

Badri, A., Boudreau-Trudel, B., Souissi, A.S., 2018. Occupational health and safety in the industry 4.0 era: a cause for major concern? Saf. Sci. 109, 403–411.

Bakhtavar, E., Yousefi, S., 2018. Assessment of workplace accident risks in underground collieries by integrating a multi-goal cause-and-effect analysis method with MCDM sensitivity analysis. Stoch. Environ. Res. Risk Assess. 32 (12), 3317–3332.

Berger, S., Miller, A., 2015. Nationalizing Empires. Central European University Press.

Birkel, H., Veile, J., Müller, J., Hartmann, E., Voigt, .K..-I., 2019. Development of a risk framework for industry 4.0 in the context of sustainability for established manufacturers. Sustainability (Basel, Switzerland) 11 (2), 384.

Büchi, G., Cugno, M., Castagnoli, R., 2020. Smart factory performance and Industry 4.0. Technol. Forecast. Soc. Change 150, 119790.

Calia, E., D'Aprile, D., 2020. Industry4.0. Springer International Publishing, Cham, pp. 309–333.

Cordeiro, G.A., Ordóñez, R.E.C., Ferro, R., 2019. Theoretical proposal of steps for the implementation of the Industry 4.0 concept. Braz. J. Oper. Prod. Manag. 16 (2), 166–179.

Cugno, M., Castagnoli, R., Büchi, G., 2021. Openness to Industry 4.0 and performance: the impact of barriers and incentives. Technol. Forecast. Soc. Change 168, 120756.

Culot, G., Orzes, G., Sartor, M., Nassimbeni, G., 2020. The future of manufacturing: a delphi-based scenario analysis on Industry 4.0. Technol. Forecast. Soc. Change 157, 120092.

Czifra, G., Molnár, Z., 2020. Covid-19 and Industry 4.0. Vedecké práce Materiálovotechnologickej fakulty Slovenskej technickej univerzity v Bratislave so sídlom v Trnave 28(46), 36–45.

Dictionary, B., 2020. Risk Definition. http://www.businessdictionary.com/definition/risk.html.

Evans, P.C., Annunziata, M., 2012. Industrial internet. Pushing the Boundaries of Minds and Machines 26.

Guo, S., Zhao, H., 2017. Fuzzy best-worst multi-criteria decision-making method and its applications. Knowl. Based Syst. 121, 23–31.

Hariharan, S., Rajmohan, M., 2019. Prioritization of risks in bicycle supply chain using fuzzy analytic hierarchy process. Int. J. Eng. Res. Technol. 8 (1), 12–16.

Hempel, J., Glemser, S., 2017. Starting the next industrial revolution in Germany.

Hofmann, E., Rüsch, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. Comput. Industry 89, 23–34.

Horváth, D., Szabó, R.Z., 2019. Driving forces and barriers of Industry 4.0: do multinational and small and medium-sized companies have equal opportunities? Technol. Forecast. Soc. Change 146, 119–132.

Ilangkumaran, M., Karthikeyan, M., Ramachandran, T., Boopathiraja, M., Kirubakaran, B., 2015. Risk analysis and warning rate of hot environment for foundry industry using hybrid MCDM technique. Saf. Sci. 72, 133–143.

Irish Department of Business, 2019. Ireland's Industry 4.0 Strategy 2020-2025, Supporti Ng the Digital Transformati On of the Manufacturing Sector and Its Supply Chain, https://enterprise.gov.ie/en/Publications/Publication-files/Irelands-Industry-4-Strategy-2020-2025.pdf.

Ivanov, D., Dolgui, A., 2020. A digital supply chain twin for managing the disruption risks and resilience in the era of industry 4.0. Prod. Plan. Control 1–14 ahead-of-print (ahead-of-print.

Jacobi, H.-.F., Landherr, M., 2013. Bedeutung Des Treibers Informations-Und Kommunikationstechnik Für Die. Digitale Produktion, p. 41.

Kamble, S.S., Gunasekaran, A., Sharma, R., 2018. Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry. Comput. Ind. 101, 107–119.

Khan, S., Khan, M.I., Haleem, A., 2020. Prioritisation of Challenges Towards Development of Smart Manufacturing Using BWM Method. Springer International Publishing, Cham, pp. 409–426.

Kiel, D., MÜLler, J.M., Arnold, C., Voigt, K.-.I., 2017. Sustainable industrial value creation: benefits and challenges of industry 4.0. Int. J. Innov. Manag. 21 (8), 1740015.

Koch, V., Kuge, S., Geissbauer, R., Schrauf, S., 2014. Industry 4.0: opportunities and challenges of the industrial internet. Strategy PwC 5–50.

Lasi, H., Fettke, P., Kemper, H.-.G., Feld, T., Hoffmann, M., 2014. Industry 4.0. Bus. Inf. Syst. Eng. 6 (4), 239–242.

Lehane, M., 2020. Govt expects covid expenditure to reach €9bn next year https://www.rte.ie/news/2020/0922/1166636-coronavirus-ireland/. (Accessed 22 September 2020).

Luthra, S., Mangla, S.K., 2018. Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. Process Saf. Environ. Prot. 117, 168–179.

Manyika, J., Chui, M., Bughin, J., Dobbs, R., Bisson, P., Marrs, A., 2013. Disruptive Technologies: Advances That Will Transform Life, Business, and The Global Economy. McKinsey Global Institute, San Francisco, CA.

Mittal, S., Khan, M.A., Romero, D., Wuest, T., 2018. A critical review of smart manufacturing & Industry 4.0 maturity models: implications for small and medium-sized enterprises (SMEs). J. Manuf. Syst. 49, 194–214.

Moeuf, A., Lamouri, S., Pellerin, R., Tamayo, S., Tobon-Valencia, E., Eburdy, R., 2019. Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs. Int. J. Prod. research 1–17.

Moktadir, M.A., Ali, S.M., Kusi-Sarpong, S., Shaikh, M.A.A., 2018. Assessing challenges for implementing industry 4.0: implications for process safety and environmental protection. Process Saf. Environ. Prot. 117, 730–741.

Müller, J.M., Buliga, O., Voigt, .K..-I., 2018. Fortune favors the prepared: how SMEs approach business model innovations in Industry 4.0. Technol. Forecast. Soc. Change 132, 2–17.

Müller, J.M., Traub, J., Gantner, P., Voigt, K.-.I., Mention, A.-.L., Torkkeli, M., 2020. Managing digital disruption of business models in industry 4.0. World Scientific Book Chapters, 47–72.

Nazam, M., Xu, J., Tao, Z., Ahmad, J., Hashim, M., 2015. A fuzzy AHP-TOPSIS framework for the risk assessment of green supply chain implementation in the textile industry. Int. J. Supply Oper. Manag. 2 (1), 548–568.

Norouzi, A., Ghayur Namin, H., 2019. A hybrid fuzzy TOPSIS – best worst method for risk prioritization in megaprojects. Civil Eng. J. 5 (6), 1257–1272.

Orzes, G., Rauch, E., Bednar, S., Poklemba, R., 2018. Industry 4.0 Implementation Barriers in Small and Medium Sized Enterprises: A Focus Group Study. IEEE, pp. 1348–1352.

Prasanna Venkatesan, S., Kumanan, S., 2012. Supply chain risk prioritization using a hybrid MCDM approach. Adv. Mat. Res. 488-489, 406–410.
Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A.B., Rajak, S., 2020. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective. Int. J. Prod. Econ. 224, 107546.
Rezaei, J., 2015. Best-worst multi-criteria decision-making method. Omega (Oxford) 53, 49–57.
Rezaei, J., 2016. Best-worst multi-criteria decision-making method: some properties and a linear model. Omega (Westport) 64, 126–130.
Samvedi, A., Jain, V., Chan, F.T.S., 2013. Quantifying risks in a supply chain through integration of fuzzy AHP and fuzzy TOPSIS. Int. J. Prod. Res. 51 (8), 2433–2442.
Sanchez, D.O.M., 2019. Sustainable Development Challenges and Risks of Industry 4.0: A Literature Review. IEEE, pp. 1–6.
Schröder, C., 2016. The challenges of industry 4.0 for small and medium-sized enterprises.
Sohrabinejad, A., Rahimi, M., 2015. Risk determination, prioritization, and classifying in construction project case study: gharb tehran commercial-administrative complex. J. Constr. Eng. 2015, 1–10.
Stentoft, J., Wickstrøm, K.A., Philipsen, K., Haug, A., 2019. Drivers and barriers for industry 4.0 readiness and practice:a SME perspective with empirical evidence.
Sung, T.K., 2018. Industry 4.0: a Korea perspective. Technol. Forecast. Soc. Change 132, 40–45.
Tupa, J., Simota, J., Steiner, F., 2017. Aspects of risk management implementation for industry 4.0. Procedia Manuf. 11, 1223–1230.
Turskis, Z., Goranin, N., Nurusheva, A., Boranbayev, S., 2019. Information security risk assessment in critical infrastructure: a hybrid MCDM approach. Informatica (Vilnius, Lithuania) 30 (1), 187–211.
Wang, X., Chan, H.K., Yee, R.W.Y., Diaz-Rainey, I., 2012. A two-stage fuzzy-AHP model for risk assessment of implementing green initiatives in the fashion supply chain. Int. J. Prod. Econ. 135 (2), 595–606.
Wee, D., Breunig, M., Tann, V.V.D., 2016. Industry 4.0 After the Initial Hype Where manufacturers Are Finding Value and How They Can Best Capture It. McKinsey & Company Inc., New York, p. 140.
Wee, D., Kelly, R., Cattel, J., Breunig, M., 2015. Industry 4.0-how to Navigate Digitization of the Manufacturing Sector. McKinsey & Company, p. 58.
Whysall, Z., Owtram, M., Brittain, S., 2019. The new talent management challenges of Industry 4.0. J. Manag. Dev. 38 (2), 118–129.
Williams, D., Tang, H., 2020. Data quality management for industry 4.0: a survey. Software Quality Professional 22, 26–35.
World Economic Forum, 2018. Readiness For the Future of Production Report 2018. World Economic Forum Geneva.
Xu, L.D., He, W., Li, S., 2014. Internet of things in industries: a survey. IEEE Trans. Ind. Inform. 10 (4), 2233–2243.
Xu, L.D., Xu, E.L., Li, L., 2018. Industry 4.0: state of the art and future trends. Int. J. Prod. Res 56 (8), 2941–2962.

Pezhman Ghadimi received the M.Eng. degree in industrial engineering from University Technology Malaysia (UTM) in 2011 and a Ph.D. degree in industrial engineering and operations management from the University of Limerick (UL), Limerick, Ireland, in 2015. From 2012 to 2015, while conducting his Ph.D. research, he was employed as a researcher at the Engineering Research center (ERC), UL, to conduct research in the area of knowledge management and product lifecycle management. He is currently employed as an assistant professor of manufacturing systems at the School of Mechanical & Materials Engineering at the University College Dublin (UCD). His-research interests span a number of areas. He has been active in sustainability, procurement, multiagent systems and operations research and in designing assessment techniques. He pursues theoretical research on the area of sustainable supply chain management and operations. He has published over 45 papers in various journals, such as *Resources, Conservation and Recycling, European Journal of Operations Research, Computers and Industrial Engineering, International Journal of Production Research* and *Cleaner Production*.

Oisin Donnelly holds a Bachelor's degree from the School of Mechanical and Materials Engineering, University College Dublin.

Kubra Sar is a Ph.D. candidate at the School of Mechanical and Materials Engineering, University College Dublin. She is a member of the UCD Laboratory for Advanced Manufacturing Simulation and Robotics. Her research interests are vehicle routing problems, reverse logistics and network design and modeling. She works on waste management issues related to the medical device sector.

Dr. Chao Wang received a Ph.D. from Beijing Jiaotong University (BJTU) in 2015 with joint training at Purdue University in 2013 and 2014. He was a postdoctoral fellow at the Center for Polymer Studies and Department of Physics of Boston University from 2017 to 2019. He is currently a professor with the College of Economics and Management, Beijing University of Technology, China. His-research interests include complexity economics, sustainable supply chains, metaheuristics, and complex networks. He has published over 70 papers in various journals, such as *Omega, Resources, Conservation and Recycling, Cities, Ecological Economics, Transportation Research Part A/D*, and *Applied Energy*.

Dr. Amir Hossein Azadnia holds a Ph.D. in Industrial Engineering from University Technology Malaysia. He is a lecturer in Operations and Supply Chain Management at Letterkenny Institute of Technology. His-research interests include decision making and optimization methods, operation management, sustainable supply chains, logistics and transportation, production planning, and strategic planning. He has published over 35 papers in various journals, such as *Resources, Conservation and Recycling, Computers and Industrial Engineering, International Journal of Production Research* and *Cleaner Production*.