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Enhancing Sustainability through Fourth Industrial Revolution Technologies: A Quantitative Study Comparing Small- and Medium-Sized Enterprises with Large Enterprises

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Abstract

The purpose of this paper is to compare small- and medium-sized enterprises (SMEs) against large enterprises (LEs) in terms of their sustainability enhancements through Fourth Industrial Revolution (IR4) technologies, specifically in the context of developing countries. This study adopted a quantitative approach. Questionnaires were distributed to Malaysian manufacturers registered under Malaysia External Trade Development Corporation MATRADE via email and in-person at the Smart Manufacturing Uprising conference in Kuala Lumpur. A total of 76 valid responses were obtained and analyzed using multiple regression. Integrated engineering systems (IES), digital automation with process control sensors, and the simulation/analysis of virtual models showed significant positive effects on LEs' sustainability. The small sample size of 76 raises generalizability issues. Thus, large-scale quantitative research is recommended to validate the relationships identified in this study. The study is among the first to identify and compare the significant relationships between IR4 technologies and sustainability enhancements among SMEs and LEs. The findings are of interest to academics as well as to public and private sector practitioners in directing resources to technologies that enhance sustainability.

Keywords: Fourth Industrial Revolution, Industry 4.0, Sustainability, Quantitative Study, Simulation

1 Introduction

The current era has brought forth the Fourth Industrial Revolution (hereafter IR4), which is also known as Smart Manufacturing or Industry 4.0 [16]. Most research linked to IR4 thus far has been conceptual in nature [17]. In particular, scarce field research has been conducted to distinguish the IR4 technologies that are suitable for small- and medium- sized enterprises (SMEs) as opposed to large enterprises (LEs). This is concerning as a small-scale survey conducted in Denmark and Germany observed that the degree of IR4 technology implementation is remarkably low in SMEs [47]. This finding was supported by a large-scale study in Denmark in 2017, which pointed out that LEs are willing to work with IR4 technologies to a larger extent than SMEs [37]. Another survey conducted in Norway concluded that the implementation level of shop floor digitalization and organizational information technology (IT) competence increases in tandem with company size [6]. Therefore, IR4 technologies' impact on SMEs and LEs is suspected to differ due to their varied level of adoption [12 and 49].

Taking the example of a developing nation, the Malaysian government provides specific incentives for SMEs to increase their competitiveness and expand capital investment instead of investment in additional foreign labor. However, the adaption of enhanced manufacturing technologies in Malaysia is still low [24-25, 27] due to high implementation costs and a lack of skilled workers [9]. Moreover, despite the strong economic impact of IR4 technologies in other countries [13 and 40], few quantitative studies have been performed on this topic in developing countries. Therefore, this quantitative study aimed to narrow the gap between the theoretical knowledge of IR4 technologies and their practical implications for SMEs and LEs in the developing country of Malaysia. The objective of this research paper was to examine how IR4 technologies impact the sustainability of manufacturing organizations, as well as to compare these impacts between manufacturing SMEs and LEs.

The research questions of this study were:

1) Which IR4 technologies impact the sustainability of SMEs?

2) Which IR4 technologies impact the sustainability of LEs?

3) Which IR4 technologies have varying impacts across SMEs and LEs?

By addressing these questions, this research contributes to bridging the literature gap on the relatively understudied area of IR4 technologies and their practical impacts on firms' sustainability. Additionally, this paper identifies and classifies the distinct impacts of each technology on manufacturing organizations based on their size, i.e., small and medium vs. large.

The remaining sections of this paper are structured as follows. The literature review focuses on the implementation of IR4 and its relationship with sustainability in emerging and developed countries. This includes a scientometric analysis to graphically depict IR4's technological trends from 2012 to 2021. In the third section, an elaboration of the study's methodology and data collection is presented. Fourth, the results and discussion section reveals the analyzed relationships and compares the results with recent empirical evidence. The final section concludes the paper with the study's implications, limitations, and suggestions for future research.

2 Literature Review

In this section an introduction to IR4 technologies and their implementation is provided firstly. Then, a scientometric analysis of articles sourced from the Scopus database is performed to examine recent trends in the research on the effects of IR4 technologies on sustainability.

2.1 IR4 Technologies in LEs and SMEs

The focal point of the current research was on the technologies of IR4 and its goals of increasing the firms' productivity and sustainability [31]. Table 1 explains the technologies related to IR4 that were examined in this study.

Table 1: IR4 Technologies

Technology	Explanation
Computer-Aided Design (CAD) Integrated with Computer-Aided Manufacturing (CAM)	CAD/CAM utilized in the production of complex shapes, and recently, 3D printing [26]
Integrated engineering systems	Exchange of information in product development & manufacturing by integrating IT support systems [16]
Digital automation with sensors	Digital automation systems detecting or measuring physical properties for monitoring through data [34]
Flexible manufacturing lines	Digital automation with sensors for product and operating conditions identification, flexible lines [8]
MES and SCADA systems	Remote monitoring and control of production through Manufacturing Execution System (MES) and Supervisory Control and Data Acquisition (SCADA) [8]
Simulation/Virtual models	Simulation/analysis of virtual models (Finite Element Analysis, Computational Fluid Dynamics, etc.) for design and commissioning [8]
Big data and analytics	Huge amounts of heterogenous data generated, collected and stored in manufacturing systems. Analyzed by data analytics tools to discover patterns and improve performance [20]
Internet of Things (IoT)	Things such as objects with sensors or actuators connected through a network [43]
Additive manufacturing	Truly digitally based process- and production-capable technology that enables design freedom [46]
Cloud services	Shared computing resources via networks [1]

2.2 Scientometric Analysis: Trends from 2012 to 2021

A keyword search was performed in the Scopus database in June 2021. The keywords used were "Industry 4.0", "Fourth Industrial Revolution", and "Smart Manufacturing", excluding "agriculture". In total, 1729 unique documents were identified from 2012 to 2021. The program CiteSpace 5.7 R5 was used to perform a scientometric analysis of these documents to graphically depict trends and results in IR4 research. The node types were reference, keyword and term. Figure 1 depicts the trends in IR4 research found in the scientometric analysis from 2012 to 2021.

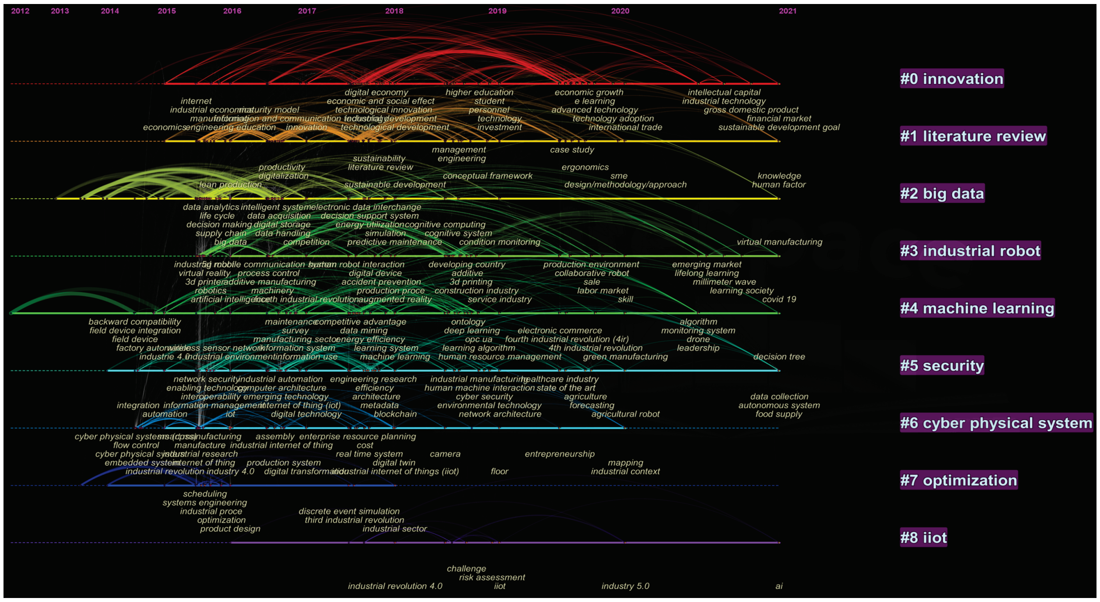

Figure 1: Scientometric analysis of IR4 clusters

The results of the scientometric analysis showed that most articles on IR4 were published between 2019 and 2021, having peaked in 2020. This shows that IR4 is a relatively new topic which is receiving growing interest. Out of the nine clusters identified in Figure 1

a) Five are IR4 technologies (big data, industrial robot, machine learning, cyber-physical system (CPS) and industrial internet of things (IIoT)).

b) Two are looking at the impact of IR4 on manufacturing (innovation and optimization)

c) One is concerned with the primary research method (literature review)

d) One examines the impact of IR4 on manufacturing, specifically its security.

Moreover, the cluster analysis in Figure 1 provides the keywords within the respective clusters. Table 2 provides the top 14 used keywords.

Table 2: Top 14 used keywords from the scientometric analysis

Keyword	Frequency	Year	Keyword	Frequency	Year
Industry 4.0	1312	2013	Industrial revolution	958	2015
Internet of thing	289	2016	Embedded system	243	2015
Cyber-physical system	172	2013	Fourth industrial revolution	160	2017
Industrial research	149	2016	Manufacture	145	2016
Artificial intelligence	137	2016	Smart manufacturing	119	2016
Manufacturing industry	109	2016	Automation	106	2015
Internet of Things (IoT)	102	2014	Big data	95	2015

Table 2 reveals a high interest in IR4. However, the naming convention Industry 4.0 is paramount. The clusters identified in Figure 1 match with the keywords listed in Table 2. Additionally, Table 2 identifies the initial year of publication. Industry 4.0 and its core technologies CPS and IoT are mentioned initially whereby IR4 is recognized thereafter.

2.3 The Impact of IR4 on Sustainability

Sustainability is defined as the reconciliation of environmental, social, and economic demands [36]. [11] distinguished between IR4 and sustainable business development; that is, IR4 facilitates a high-tech competitive advantage but not necessarily a sustainable business model. However, it can do both by preserving natural resources and incorporating sustainability in the business model [11].

The relationship between IR4 and sustainability has generally been identified as positive in recent literature [2, 18]. [39] explained that IR4 will make firms' value creation more sustainable. Specifically, it contributes to the environmental dimension of sustainability by allocating material, energy, and water resources more efficiently. At the micro level, IR4 technologies that provide opportunities for sustainable manufacturing are information communication technologies and cyber-physical systems [39].

In fact, [38] qualitatively assessed the micro and macro impacts of IR4 on ecological and social indicators. With reference to ecological factors, they identified the positive effect of IR4 on resource management, emissions, and water management. However, in terms of energy management, they projected primary energy consumption to increase following IR4, leading energy efficiency to show ambiguous results. In terms of social indicators, IR4 was revealed to have a positive impact on publicity and social acceptance. The study concluded that IR4's power lies in improved working conditions at product, process, equipment, human, resource, and organizational levels, although higher quantities of materials are used at the product level [38].

In contrast to [38], [14] surmised that the IR4's primary focus on sustainability is to reduce energy consumption. They pointed out that energy consumption is a critical contributor to overall manufacturing costs and hence must be monitored [14]. Supporting [38], [7] found that IR4 contributes to sustainable industrial value creation as well as to the environmental dimension of sustainability. On top of that, the design principles of IR4 are seen to improve sustainable manufacturing. It is predicted that longer machine life cycles, decreased industrial waste, increased recycling opportunities, and better use of resources contribute significantly to more sustainable manufacturing in the IR4 era [7].

A unique approach was taken by [15] by connecting keyword clusters of environmental protection, process safety, and IR4 technologies. In contrast to other publications, they revealed a relationship between the keywords of sustainability and smart manufacturing. Furthermore, environment, air pollution, and water quality were linked to IR4 technologies like big data, cloud computing, IoT and cyber-physical systems [15].

CNI conducted a large-scale quantitative study on the relationship between sustainability and IR4 in Brazil. The results showed that 22% of LEs, 18% of medium-sized firms, and 10% of small firms expect increased energy efficiency. However, only 8% of the respondents foresee improved sustainability through the adoption of IR4 technologies [8]. This survey data was further analyzed by [9], whose rotated factor-loading matrix from their Principal Component Analysis (PCA) reported that improved sustainability has a high and positive factor loading in terms of IR4 side-effects [9]. These findings were supported by 21 expert interviews from Brazil's plastics industry. The respondents predict positive impacts from the IoT and smart sensors on energy efficiency, occupational health and safety as well as water and raw material consumption [30].

Overall, the literature identified a positive relationship between IR4 and sustainability's environmental, economic and social dimension.

3 Methods

A quantitative approach was adopted in this study. A close-ended survey questionnaire was designed with validated scales and distributed via email using the MATRADE database between January and March 2019. The questionnaire was also distributed personally at the Smart Manufacturing Uprising conference in April 2019 in Kuala Lumpur, Malaysia. A total of 40 valid responses were obtained through email while 36 valid responses were obtained in-person. The measures for the independent variables (IR4 technologies) were derived from CNI's (2016) survey, which were used by [9]. The dependent variable 'sustainability' was measured using items sourced from [48]. The items were rated on a five-point Likert scale as well, ranging from 'strongly disagree' to 'strongly agree' in terms of IR4's positive effect on each sustainability dimension, i.e., water consumption, energy consumption, waste, consumption of hazardous materials and pollution. A pilot test was conducted to confirm the items' reliability. The result revealed that the Cronbach's alpha of sustainability was 0.910. Hence, the questionnaire was assumed to be reliable.

Using IBM's Statistical Package for the Social Sciences (SPSS) version 25.0, the collected data was analyzed in the form of descriptive and inferential statistics. Only questionnaires that were at least 80% complete and had indicated firm size were considered for analysis. One questionnaire that did not mention the company size was excluded, resulting in a final balanced data set of 39 SME responses and 37 LE responses. The dependent variables had skewness and kurtosis values below 2.0. Therefore, the data's normal distribution was assumed during the analysis. The independent and dependent variables are listed in Table 3. The independent variables comprised 10 IR4 technologies whereas the dependent variable is the expected benefits of the technologies in terms of sustainability gains.

Table 3: Independent and dependent variables

Independent Variables (Technologies)	
IV01: Computer-Aided Design integrated with Computer-Aided Manufacturing (CAD/CAM)	IV02: Integrated engineering systems (ENG_SYS)
IV03: Digital automation with sensors (SENSORING)	IV04: Flexible manufacturing lines (FLEXIBLE)
IV05: MES and SCADA systems (MES/SCADA)	IV06: Simulation/Virtual models (SIMaVM)
IV07: Big data and analytics (BIG_DATA)	IV08: Internet of Things (IoT)
IV09: Additive manufacturing (ADDITIVE)	IV10: Cloud services (CLOUD)
Dependent Variable (Expected Benefits)	
DV01: Sustainability	

The following section discusses the results of the descriptive analysis and multiple regression analysis to explain the relationships between the variables.

4 Results and Discussion

4.1 Descriptive Analysis

Overall, a majority of the respondents were males between 36 and 45 years old. Most of the SME respondents held founder or CEO positions, while most of the LE respondents held managerial or executive positions. Indicating a stark contrast between both sample groups, nearly all the SMEs in this study were small enterprises with less than 100 employees whereas most of the LEs had over 2000 employees.

4.2 Independent Samples t-Test

To detect the statistical difference between the means of each IR4 technology's user and non-user, an independent samples t-test was deployed separately for SMEs and LEs. Cut points 1 and 2 were determined for both groups. Cut point 1 included sustainability dimensions but did not take into account the expected benefit of boosting Malaysia's sustainability competitiveness. Cut point 2 takes both into consideration.

Table 4 shows the independent samples t-test result. Only significant results are displayed. Integrated engineering systems, simulation and digital automation with process control sensors have a significant relationship with higher sustainability for LEs.

Table 4: Independent Samples t-Test for LEs using cut point 1 for simulation, cut point 2 for integrated engineering systems and group 1=0 and group 2=2 for digital automation with process control sensors

Technology Test	Integrated engineering systems	Simulation/Analysis of virtual models	Digital automation with process control sensors
Levene's Test	Significance 0.041	Not significant	Not significant
t Test for equality of means equal variances assumed		Significance 2-tailed 0.048 for LEs	Significance 2-tailed 0.025 for LEs
t Test for equality of means unequal variances assumed	Significance 2-tailed 0.000 for LEs		

4.3 Discussion of Results

Integrated engineering systems, simulation, and digital automation with process control sensors were identified as significant technologies for LEs' sustainability. These relationships are discussed in the following sections in relation to the extant literature. In this section, the identified IR4 technologies related to sustainability, i.e., integrated engineering systems, simulation/analysis of virtual models, and digital automation with process control sensors, are reviewed.

4.3.1. Integrated Engineering Systems and Sustainability

Integrated engineering systems have a positive relationship with sustainability, according to [35] "better performing than engineered" mechanism. An IT support system self-optimizes the production process and increases its quality level. In doing so, it steps up resource efficiency and establishes sustainable manufacturing processes [35]. However, other studies have not backed up the claim that integrated engineering systems enhance firm sustainability [41 and 42]. Hence, the limited evidence does not offer much support to this study's result. Here the limitation is the number of studies conducted examining the impact of integrated engineering system on LE's sustainability.

4.3.2. Simulation/Analysis of Virtual Models and Sustainability

[10] analyzed virtual models in the automotive industry, where once CAD models are available, physics-based simulations are conducted. They found that energy components and energy systems are modeled to produce energy efficiency improvement measures. Afterwards, energy-efficient physics-based system models are evaluated quantitatively in terms of energy savings. Out of that, an energy-efficient system design is accomplished. Thus, increased sustainability of the assembly system in the automotive industry is realized via extensive simulation [10]. Supporting [10], [35] alleged that simulation and virtual models improve a firm's sustainability. Taking the example of extrusion mold die design optimization, algorithms are applied to identify the optimal simulated die. This reduces material consumption compared to the previous manual, iterative process of mold design based on experience [35]. Moving forward from die casting and extrusion to snack manufacturing, [29] claimed that simulation of the facility layout improves energy efficiency and reduces waste. Complementary to the positive relationship identified in these studies, [7] discussed how IR4 design principle virtualization decreases waste and thus improves sustainability. Overall, the literature comprehensively implies a positive relationship between simulation and sustainability gains.

4.3.3. Digital Automation with Process Control Sensors and Sustainability

A distinct relationship between the energy-saving dimension of sustainability and automation with process control sensors was identified in energy-efficient building automation in the production environment. For example, in a tool production facility, temperatures should not vary by even one degree during operations. Through the installation of eight temperature sensors in the production building, the thermal dynamics could be observed. The observation was enhanced by a Nonlinear Model Predictive Control (NMPC) developed in MATLAB to optimize the energy consumption of heating, cooling, and ventilation. In addition, weather forecasts were included to predict future outdoor temperature influences. Due to such advanced control the air conditioning, heating, and ventilation, time was reduced significantly and great energy savings were realized [50]. Also touching on energy savings in factories, [32] proposed to thermally link industrial plants to reduce heat waste, improve energy efficiency, and increase flexibility through thermal storage capacities and interaction with other energy networks. In this scenario, the present temperatures in a respective area would be measured by temperature sensors and transferred to a centralized PLC. By doing so, the overall energy consumption to regulate factory temperature can be reduced significantly [32]. Hence, in terms of building temperature regulation, digital automation with process control sensors achieves energy savings. However, such automation has not been linked to reduced water consumption, pollution, consumption of hazardous materials, and disposal costs. [19] presented an automation pyramid, starting from Level 0 (the production process), to Level 1 (sensing and actuation), Level 2 (monitoring, supervision, and control), Level 3 (manufacturing operations) and finally, Level 4 (business planning and logistics). They proposed to extend the pyramid and integrate factories into the power grid by enabling factories to share energy demands with their power supplier. This information enables the energy supplier to adjust the primary energy supply in response to actual demand, which saves electrical energy. Thus, automation with process control sensors and energy savings have a strong relationship. This is further supported by the IEC 61599 standard which takes sustainability into account during the design of automation systems [23].

4.3.4. Comparison with other Quantitative, Qualitative and Case Studies

Table 5 lists the results of 10 studies in the manufacturing environment of the identified impact on firm's sustainability. The studies are sorted by year of publication. Process control sensors, smart sensors, sensors and actuators are grouped under sensors. This quantitative study is listed as Malaysia. Quantitative, qualitative and case studies are included.

Table 5: Comparison of IR4 studies indicating countries

Country, authors	IES	Sensors	Simu-lation	AI	Block-chain	IoT/ IIoT	CPS	Mobile tech.	Cloud	Big data
Malaysia	+ LE	+ LE	+ LE							
World, [3]		+	+		+	+		+	+	+
India, [33]		+								
China, [21]									+	
Numerous, [44]				+						
China, [45]				+						
Malaysia, [28]										+
China, [22]							+			
China, [5]						+				+
China, [4]						+				

Table 5 illustrates that various quantitative, qualitative and case studies have been performed in recent years. In a nutshell, all findings in our quantitative sutdy are supported by reviewing recent studies except the claim that IES enhances the sustainability of LEs.

5 Conclusion

This study found that integrated engineering systems, simulation, and digital automation with process control sensors are important IR4 technologies to enhance LE's sustainability. Nonetheless, this paper failed to provide evidence on seven of the 10 IR4 technologies as predictors of sustainability enhancement. Not even one IR4 technology has a significant impact on SMEs sustainability. This is caused by the low level of implementation of IR4 in SMEs. Thus, large-scale surveys are recommended to test these relationships with a clear distinction between SMEs and LEs. However, despite its limited findings, the paper contributes to an initial understanding of the key differences between SMEs and LEs in the application and role of IR4 technologies.

5.1 Practical Implications

Despite the small scale of this study, significant differences were observed between SMEs and LEs in terms of their IR4 technologies, thereby offering valuable insights to these firms. In particular, the study names specific IR4 technologies that impact sustainability for LEs, especially highlighting that potential sustainability achievements through IR4 technologies differ between SMEs and LEs. Depending on the size and level of IR4 readiness of an organization, suitable technologies may vary tremendously. The ultimate contribution of IR4 to enhance sustainability further depends on technological, economic, and social dimensions, as well as the company's culture and willingness to change. Therefore, this study reveals distinct relationships between IR4 and sustainability enhancements, with an emphasis that these relationships are subject to the respective organization.

5.2 Managerial, Policy and Theoretical Implications

The paper supports the argument that not all technologies have a positive impact on sustainability in a respective organisation. Thus, decision makers are recommended to carefully examine company size, industry, readiness, and facility stage before launching the implementation of IR4. Based on this quantitative study, policy makers should enhance national IR4 policies by conducting large-scale, industry-specific surveys aimed to direct resources to the most promising technologies. The first step towards directing resources has been accomplished by the present study. The theoretical contribution of this paper is its distinction between SMEs and LEs in examining the impacts of 10 IR4 technologies. The differing relationships between specific IR4 technologies and sustainability were identified by company size. This implies that the recommendation of specific IR4 technologies depends on firms' size and level of development.

5.3 Limitations and Future Research

This quantitative study consisted of only 76 responses, which does not imply generalizability to other sectors. The results obtained in this study should hence be confirmed by large-scale quantitative studies to provide more substantial evidence on the identified relationships. The next limitation is that the data was not obtained from a single group of respondents, raising issues of a heterogenous sample. Moreover, given that implementing and observing the results of IR4 technologies is a relatively long process, the cross-sectional nature of this study may not have captured the respondents' actual opinions over time. Lastly, the study was conducted in Malaysia, where culture-specific factors may have impacted the responses. Future research may consider a larger, more homogenous sample, a longitudinal design, or a more culturally diverse sample when studying IR4 technologies.

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