Chapter 6

Assessing the Critical Role of ICT in Improving the I4R for Circular Economy

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CHAPTER 6

Assessing the Critical Role of Information and Communications Technology in Improving Industry 4.0 Readiness for the Circular Economy

Premaratne Samaranayake

1. Introduction

TIn recent times, Industry 4.0 (I4), referred to as 'the fourth industrial revolution characterised by a paradigm shift from centrally controlled to decentralised production processes' (Hermann, Pentek, and Otto, 2016, p.3929), has attracted significant attention across the globe, including from emerging economies, from the government level to practitioners and researchers (Hermann, Pentek, and Otto, 2016; Ramanathan, 2016; Liao et al., 2017). An investigation into various aspects of I4 includes studies on the characterisation of I4 through a systematic literature review (Liao et al., 2017); implementation and/or transition to I4 with a range of foci, mainly at the firm level (Hermann, Pentek, and Otto, 2015; Weyer et al., 2015; Ramanathan, 2016; and Samaranayake, Ramanathan, and Laosirihongthong, 2017); comprehensive reviews of current practices and future directions (Wang, Törngren, and Onori, 2015; Qin, Liu, and Grosvenor, 2016; Hofmann and Rusch, 2017; Lu, 2017; Liao et al., 2017; Pagoropoulos, Pigosso, and McAloone, 2017; Moeuf et al., 2018); and, more recently, on Industry 4.0 readiness (I4R) at the firm level, focusing on the circular economy (CE) (Ramanathan, 2016; Stock and Seliger, 2016; Waibel et al., 2017; Trentesaux et al., 2016).

Many studies on the implementation and/or transition to I4 have reported on different perspectives of practices and outcomes, including the drivers, barriers, initiatives, and success factors (Wang Törngren, and Onori, 2015; Liao et al., 2017) as well as implications for the industry (Hofmann and Rusch, 2017). It is evident from these studies that the main focus has been on technology, in particular the characterisation of the key components of I4, current industry practices, and future directions (Hofmann and Rusch, 2017; Liao et al., 2017). With increasing interest in I4 and the focus on CE in manufacturing broadly in recent times by both developing and emerging economies, many research initiatives have investigated how the principles of CE can be deployed by I4 (de Sousa Jabbour et al., 2018) and how I4 can enable CE at the firm level (Ramanathan, 2018). This brings us to the point of departure from the literature on the current level of I4R for CE at the firm level, with an indication of limited studies focusing on the sector and industry-specific levels.

While implementation/transition to I4 at the firm level has been studied and reported, with an emphasis on CE principles, the importance of understanding the current level of maturity in the industry context is emphasised (Bibby and Dehe, 2018). The need for assessing I4R for CE from information and communications technology (ICT) perspectives at the firm and sector levels is also emphasised due to the increasing level of industry-specific supply chain practices focusing on circular economies and the close relationships between I4 technology components and ICT systems. Thus, this chapter extends the current knowledge of I4 practices at the firm level by exploring I4R for CE focusing on the firm and industry/sector levels, emphasising the critical role of ICT systems as one of the determinants of assessing I4R (Ramanathan 2018).

Therefore, the key objectives of this study are:

(i) Provide guidelines for assessing the critical role of ICT systems in improving I4R, focusing on both firm- and sector-level applications of ICT systems.
(ii) Identify and emphasise the measurable parameters of I4R for CE from the perspective of the critical role of ICT.

(iii) Describe trends for shaping the future manufacturing landscape and provide some guidelines on how Association of Southeast Asian Nations (ASEAN) policymakers and businesses can prepare for the change, using the analysis associated with objectives (i) and (ii) above.

Guidelines for assessing the critical role of ICT systems in improving I4R for CE, from ICT systems perspective at the firm and industry/sector levels to the measures and parameters of the assessment framework, are explored from a theoretical background concerning the key concepts of I4, CE, and industry sectors, as well as the characterisation of ICT systems, with a particular focus on firm- and industry-specific ICT systems and their relation to measuring I4R for CE.

This chapter proposes a framework for the assessment of I4R for CE from the ICT systems perspective. The framework is based on the key principles of I4 and CE, an overview of industry sectors from the perspective of I4, and the key requirements for I4R, focusing on CE across firms and industry/sector levels. This is followed by trends for shaping the manufacturing landscape, implications for policy/decision makers, and examining how businesses can prepare for the potential change. In addition, this chapter presents parameters and measures as part of the framework for assessing the critical role of ICT in improving I4R for CE at the firm and industry/sector levels and reports on how the assessment framework can be developed and guided by the principles of both themes (I4 and CE). It is expected that the complex dynamics of I4 and CE will lead to the need for careful investigation on how both work together at the firm, industry/sector, and national levels.

2. Research Background

2.1. Industry 4.0 and the Circular Economy

There has been a substantial amount of academic research and industry-driven exploratory/investigatory work reported in the literature on I4 from various perspectives since its inception in 2011 (Hermann, Pentek, and Otto, 2016). These studies cover a range of topics, including a comprehensive literature review on current practices and potential future directions (Lu, 2017; Liao et al., 2017), the current status and latest developments of various systems of I4 (Wang et al., 2015), and implementation perspectives from frameworks and I4 industry-specific applications (Qin, Liu, and Grosvenor, 2016; Stojkić, Veža, and Bošnjak, 2016; Dada and Thiesse, 2008). In addition, studies have investigated other aspects, including technologies and key components (Kang et al., 2016; Zhong et al., 2017; Hofmann and Rusch, 2017); characteristics, including interoperability (Lu, 2017) and integration (Kagermann, Wahlster, and Helbig, 2013; Chen, 2017); the application of technologies with increased performance (Trentesaux, Borangiu, and Thomaset, 2016); communication with customers in real time (Shrouf et al., 2014); and the relationships with sustainability and CE (de Sousa Jabbour et al., 2018; Fisher et al., 2018).

Many research studies have identified the key components and technologies of I4, including cyber-physical systems (CPS), cloud computing, Internet of Things (IoT), additive manufacturing, and Internet of Services (IoS) (Hermann, Pentek, and Otto, 2016; Hofmann and Rusch, 2013; de Sousa Jabbour et al., 2018). These key components and technologies have been studied from a range of perspectives, including the CPS of integrated computer and ICT systems as the basis for developing cyber-physical production systems (CPPS) leading to I4 (Monostori et al., 2016) and the advancement of CPS in manufacturing, reflecting on the increasing openness, autonomy, distributed control, adaptability, and degree of integration through a number of examples (Wang et al., 2015). Furthermore, IoT as a key component has been used in various ways for the advancement of manufacturing in recent times, in particular I4 and smart factories as part of the IoT and IoS (Kang et al., 2016) and smart production systems integrating the virtual and physical worlds on IoT platforms (Waibel et al., 2017).

Amongst the latest developments and future directions of I4 reported in recent times, I4 for CE has attracted increased attention from both academics and industry practitioners. This is from a range of research investigations on various aspects, including sustainable development (McDowall et al., 2017), regulations to implement CE principles to encourage organisations to pursue CE principles (Winans, Kendall, and Deng, 2017), and very recently on a roadmap for sustainable operations, supported by I4 (de Sousa Jabbour et al., 2018).

Recently, de Sousa Jabbour et al. (2018), using a roadmap to enhance the application of CE principles in organisations by means of I4 approaches, presented a matrix of relationships between CE, I4, and sustainable operations management and highlight the connections between the individual steps of CE principles (MacArthur, Zumwinkel, and Stuchtey, 2015) using components of I4 across the product life cycle.

Studies on concepts and principles of CE are emphasising sustainability in different forms, including sustainable production and consumption (Fahimnia et al., 2017), the sustainable use of natural resources (McDowall et al., 2017), maximising the circularity of resources and energy within production systems (Ghisellini, Cialani, and Ulgiati, 2016), the extension of a product's lifespan through a hierarchy of circularity strategies (Zhao and Zhu, 2017), and transforming waste into resources for other production systems (Bocken et al., 2017; Murray, Skene, and Haynes, 2017).

When considering CE principles for the purpose of I4, MacArthur (2015) outlined three principles to govern the CE cycles and proposes six business actions, labelled the 'ReSOLVE' framework, to guide organisations through implementing the principles of CE (de Sousa Jabbour et al., 2018). The principles and the framework for implementing the CE principles proposed by MacArthur, Zumwinkel and Stuchtey (2015) are adopted in this research as the basis for identifying the critical role of ICT systems in implementing I4 for CE. One of the limitations of current I4R assessment frameworks is that assessment is focused mainly at the firm level and not on the sector/industry levels. In order to develop a framework for assessing I4R for CE at the firm and industry/sector levels from the perspective of ICT, we next consider and briefly outline the theoretical background regarding industries/sectors and the associated ICT systems.

2.2. Industries/Sectors and ICT Systems at the Firm and Industry/Sector Levels

All three sectors (primary, secondary, and tertiary) consist of various industries and are an integral part of any economy, producing goods and services for local and global consumption. Some industries can be considered as a combination of more than two sectors, with possible crossovers depending on the nature of production and the products and services involved. Each sector is supported by a range of processes

and systems. In this case, key processes associated with any industry sector can be categorised into two distinct areas: IT-based processes and manufacturing processes. ICT-based and manufacturing processes are interrelated and connected through the respective systems and communication technologies. From the system perspective, IT-based and manufacturing processes are facilitated through ICT systems, such as enterprise resource planning (ERP) systems (also called enterprise systems) and manufacturing systems, respectively. From the operational perspective, enterprise systems within broader ICT systems play a significant role in any industry, given ICT systems are critical resources for any organisation.
It can be noted from the classification of the industry sector from the ICT systems perspective, in particular enterprise systems (SAP AG, 2018), that organisations can have very unique requirements of ICT systems, depending on various factors, including the nature of the products and services they produce and the type of sector and associated industry that they belong to. Furthermore, it is evident from the industry classification by ICT systems that enterprise systems have evolved into providing not just ICT systems supporting ICT-based processes at the firm level, but also ICT systems with industry-specific solutions for a range of industries (SAP AG, 2018).

Since ICT systems for functional applications at the firm and industry/sector levels play a significant role in providing integrated ICT-based processes and operational data and information within the organisation and organisations in the supply chain, assessing the critical role of ICT in improving I4R for CE is guided by measures and parameters associated with assessment criteria within ICT systems and the data management determinants of the proposed framework (Ramanathan, 2018).

In the context of the ICT systems perspective, enterprise systems provide process and data integration at the firm level (e.g. application modules of enterprise systems, system access through a firm-level intranet, and electronic data interchange) and at the industry/sector level (e.g. industry-specific enterprise solutions, supported by other applications, such as supplier relationship management (SRM), customer relationship management (CRM) and strategic enterprise management (SEM) for information-sharing with suppliers, customers, and stakeholders (Shehab et al., 2004).

While various systems at the firm level facilitate connections amongst organisations in the supply chain, it is also necessary to assess the critical role of ICT systems for improving I4R for CE at the industry/sector level. In this case, parameters and measures for the assessment of the critical role of ICT in improving I4R for CE are considered at both the firm and industry/sector levels, emphasising how the measures at both levels are defined and evaluated, and how the level of readiness at the firm level can influence readiness at the sector/industry level.

3. Methodology

The methodology for assessing the critical role of ICT systems in improving I4R for CE consists of three stages: (i) identifying the critical role of ICT systems in improving I4 for CE; (ii) developing a framework for assessing the critical role of ICT systems based on the broader framework (Ramanathan, 2018) by incorporating both firm and sector/industry level parameters and measures; and (iii) illustrating the proposed framework by incorporating a measurement tool for assessing the critical role of ICT in improving I4R for CE at the firm and industry/sector levels, taking measures and parameters at the firm and industry/sector levels into consideration.

In order to identify the critical role of ICT in I4R for CE, the relationships amongst I4, CE, and ICT systems are discussed using a comprehensive literature review of contemporary studies. Identification of the critical role of ICT will enable answering the question: What is the role of ICT in I4R and CE? In addition, this research involves the evaluation of current I4 practices in the CE as a way of answering the question: What trends will shape the future manufacturing landscape? This involves identification of the technologies of I4, their adoption in the CE, and the relationships between I4 and CE from the perspective of ICT systems. Furthermore, guidelines for policy/decision makers for the potential change are presented based on the critical role of ICT systems and the framework for assessment at the firm and sector/industry levels, highlighting the required and necessary steps for the transition to I4 through assessment of the current status and plans for the implementation.

4. Critical Role of ICT Systems in Industry 4.0 Readiness for the Circular Economy

Since the main focus of this research is to assess the critical role of ICT systems, ICT systems are outlined and discussed from the applications perspective on their relationships and the overall ICT systems portfolio of any organisation, in particular organisations as part of the supply chain (representation of industries), prior to identifying the critical role of ICT systems in improving the I4R. ICT systems cover a range of applications at the firm and industry/sector levels, including basic office/desktop applications (e.g. email and workflow), enterprise systems for ICT-based process and data integration, communication networks/systems (e.g. mobile networks and wireless networks) and internet technologies. All these systems can be part of an integrated system environment and are supported by various forms of technology infrastructure available at the firm and industry/sector levels (Wollschaeger, Sauter, and Jasperneite, 2017). In this context, the proposed framework for assessment is guided by examples of ICT systems, such as enterprise systems (integration of data, process, and applications across the organisation) and the associated communication technologies for the integration of systems across organisations. For example, Table 6.1 shows some examples of ICT systems (e.g. enterprise systems) that can be used as the basis for assessing I4R for CE.

Table 6.1: Examples of ICT Systems at the Firm and Industry/Sector Levels, Categorised by Key Criteria for Assessing Industry 4.0 Readiness

	Information Sharing	Cloud Storage, IT and Data Security	Operations Data	Virtualisation
Firm Level	Enterprise system with functional modules (Shehab et al., 2004)	Cloud storage of enterprise system data, cloud-based applications for data and IT security	Transaction data in enterprise systems (e.g. purchase orders and sales orders) (SAP AG, 2018)	Server virtualisation using
Sector/Industry Level	Enterprise systems with functional and other modules (e.g. advanced planner and optimiser, CRM, SRM, SEM), industry-specific enterprise system solutions (SAP AG, 2018)	Cloud storage of supply chain data, cloud-based applications for data warehousing, big data and analytics	Transaction data in SRM, CRM, and SEM systems (e.g. consignment orders, vendor-managed inventory status, available to promise data)	Network virtualisation using Internet of Things (IoT)

CRM = customer relationship management, IT = information technology, SEM = strategic enterprise management, SRM = supplier relationship management.
Note: Criteria sourced from Ramanathan (2018).
Source: Author.

A recent review of I4 technologies has categorised various research studies into key research categories, including (i) concepts and perspectives of I4, (ii) CPS-based I4, (iii) interoperability of I4, (iv) key technologies of I4, and (v) applications of I4 (Lu, 2017). It is evident from this review that there are a significant number of research studies on the key technologies and applications of I4 (47 out of 88). Similarly, many other studies have identified key I4 technologies, including four core technologies identified by Kang et al. (2016). Those core technologies include CPS, IoT, cloud manufacturing, and additive manufacturing and are described using the key concepts of I4 and resources associated with each technology (de Sousa Jabbour et al., 2018; Lu, 2017). It is noted from the description of these technologies in different applications that these core technologies are supported by highly developed automation and digitisation processes using communication and information technologies where IoT, CPS, ICT, and enterprise integration are closely related (Lu, 2017; Roblek, Meško, and Krapežet, 2016; Haddara and Elragal, 2015). Since these relationships are common and have been identified in various studies, the critical role of ICT systems in the CE is explored from the perspective of relationships amongst technologies, followed by other studies in key areas including literature reviews (review frameworks) and characteristics.

4.1. Relationships between I4 Key Technologies and ICT Systems

Technologies identified as core for I4 are closely related to a range of processes and resources (Kang et al., 2016). Similarly, processes, supported by data for execution using various resources, are the core of enterprise systems (Shehab et al., 2004). Since enterprise systems are an integral part of ICT systems and play a significant role in both the processes and resources, which also are an integral part of I4 technologies, there is a strong connection with ICT for the effective implementation of I4 technologies. For example, CPS, such as controllers and sensor systems, can be directly linked to production processes through enterprise systems for the automation and monitoring of manufacturing in real time (Monostori et al., 2016). In this case, the critical role that enterprise systems play includes the connection between production processes within enterprise systems as the basis for real-time monitoring of the process using sensors for quality control (e.g. detecting defects through temperature measurement).

Apart from the connection between ICT systems and I4 technologies through processes and resources, some resources are clearly part of ICT systems, such as the internet as a resource of cloud computing (Kang et al., 2016). Information generated from real-time data through some of the resources of I4 technologies is directly supported by ICT systems, such as enterprise systems (Stojkic et al., 2016). Furthermore, the relationships are identified at various levels and means, including ICT systems' connection for implementing I4 technologies (Hermann, Pentek, and Otto, 2016) and the integration of ICT systems with I4 technologies at various levels and across different applications and frameworks for assessing I4R at firm levels (Lu, 2017). The direct relationships between key I4 components and ICT systems are evident from a range of research activities, including critical reviews of I4 components indicating the physical networks of interconnected components, the cyber-networks of intelligent controllers and communication links (Hofmann and Rusch, 2017), and I4's close relation with IoT, CPS, ICT, enterprise architecture (EA), and enterprise integration (EI) (Lu, 2017).

It is also evident from research studies on smart systems prior to the concept of I4 that intelligent manufacturing using smart, safe, and sustainable systems emphasises the importance of the interoperability of smart systems with existing ICT systems, including enterprise systems for ensuring the viability of smart solutions in manufacturing (Alsafi and Vyatkin, 2010). This suggests that ICT systems such as enterprise systems are fundamental for the effective and efficient application of safe, smart, and sustainable systems.

The level of integration/facilitation can be used as the basis for supporting close connections amongst those components/technologies. This is evident from various studies, including on (i) the integration of systems through communication using ICT systems and the storage of large amounts of data using ICT systems (de Sousa Jabbour et al., 2018), (ii) ICT facilitating the integration of emerging technologies in I4 technologies (Zhong et l., 2017), (iii) facilitating smart manufacturing that is supported through the introduction of various ICT technologies and convergence with the existing manufacturing technologies (Kang et al., 2016), (iv) the integration of 10 major technologies for integrated and intelligent manufacturing, in particular three levels of integration (vertical, horizontal, and end-to-end) supported by the respective ICT systems (e.g. enterprise systems for vertical integration at the organisation level) for the effective and efficient use of resources across the supply chain (Chen, 2017), and (v) the need for three levels of integration supported by ICT systems for the realisation of I4 (Kagermann, Wahlster, and Helbig, 2013).

Recently, Lu (2017) identified the main characteristics of I4, which include integrated, adapted, optimised, and interoperable manufacturing processes. Integrated and interoperable manufacturing processes are directly linked with materials-planning and the production (the execution of plans) processes of enterprise systems, supported by ICT systems, such as service-oriented architecture for application distribution, networking for three-tier architecture, and database technology for data integrity and real-time data maintenance (Monostori et al., 2016).
Recently, Zhong et al. (2017) highlighted the significance of ICT in smart and intelligent manufacturing, and outline current applications of ICT that focus on the integration of the technologies of I4, such as IoT and CPS. Some examples of ICT systems associated with I4 technology are presented in Table 6.2.

Table 6.2: Relationships between I4 Principles, Technology, and ICT Systems

Principles of Industry 4.0 (I4)	Description	Examples – I4 Technology, Process(es) and Data	Related ICT Systems	ICT Activity/Process
Integration (Wang et al., 2015), integrated manufacturing (Chen, 2017)	Integration of physical things and devices (materials and machines), with the ability to process a large range of data, information, and knowledge in real time (Chen, 2017)	Prioritisation of production orders through the integration of CPS, physical processes, and objects in production lines (Ahmadov and Helo, 2018; Lee et al., 2015)	Sensors and actuators (Yu et al., 2015). Vertical integration using technologies such as the manufacturing execution system and computer-aided process planning (Chen, 2017)	Gathering and distributing real-time data using sensors and actuators (Yu et al., 2015) Real-time data update using three levels of integration in manufacturing: vertical integration, horizontal integration, and end-to-end integration (Kagermann et al., 2013)
Interoperability	Synthesises software components, application solutions, and business processes (Berre et al., 2007)	Data interoperability: seamless exchange of electronic product, process, and project data is enabled through the interoperable data systems used by collaborating divisions or companies and across design, construction, maintenance, and business systems (Kang et al., 2017)	Data systems of business systems (Kang et al., 2017)	Real-time manufacturing information-capturing through sensor-embedded manufacturing resources and IoT architecture based on real-time manufacturing information integration services (Zhang et al., 2015)

Principles of Industry 4.0 (I4)	Description	Examples – I4 Technology, Process(es) and Data	Related ICT Systems	ICT Activity/Process
Intelligence (Qin et al., 2016; Chen, 2017)	Intelligent manufacturing using intelligent systems, through the power of computing intelligence to enhance the decision-making process in manufacturing (Chen, 2017)	Mobile CPS has emerged with advances in cloud computing and wireless sensing technologies (Chen, 2017)	Current applications of ICT focus on integration with other technologies, such as cloud computing and the IoT, so that the existing information systems can be combined with cutting-edge technologies (Zhong et al., 2017)	Information systems connected with cutting-edge technologies.

CPS = cyber-physical systems, ICT = information and communication technology, IoT = Internet of Things.
Source: Author.

Various literature review-based studies on I4 concepts and technologies and the relationships between I4 components and ICT systems are highlighted using both the outcomes of the literature reviews and the frameworks being used for the literature reviews. In the case of outcome-based studies, from a systematic literature review of digitisation and automation in the context of I4 in the construction industry, Oesterreich and Teuteberg (2016) conceptualised the impact of I4 technologies on the construction value chain. The conceptual model clearly shows both horizontal and vertical integration of key I4 components, including digitisation and virtualisation through various ICT components and vertical integrated organisational processes, supported by ICT systems, such as enterprise systems. From a systematic literature review on the past, present, and future of I4, Liao et al. (2017) identified three necessary integration points for the realisation of I4, for which each integration point is clearly related to the integration of various I4 components with ICT systems.

Recently, Moeuf et al. (2018) used an analytical framework of key I4 technologies as the basis for a scientific literature review of I4. The proposed analytical framework confirms ICT systems to be a key component/technology of I4.

For example, big data and analytics, simulation, virtual reality, and cybersecurity are directly related to ICT systems as vehicles for implementation. In addition, Qin et al. (2016), emphasising integration as a part of the intelligence level of the manufacturing framework for I4, identified three levels of automation, including process automation attributed to an automated labour force and optimised production efficiency using ICT systems.

Similarly, the framework of interoperability of I4 proposed by Lu (2017) indicates relationships between I4 components (CPS and CPPS, and associated smart concepts/objects) and ICT systems. In this case, the interoperability of I4 is referred to as the ability of two systems to understand each other and use the functionality of one another, and represents the capability of two systems exchanging data and sharing information and knowledge (Berre et al., 2007; Lu, 2017).

Most of the studies on relationships from applications of I4 perspectives have emphasised the information flow using ICT systems. Recently, Hofmann and Rusch (2017), using a logistics-oriented I4 application model, indicated that there exist several ICT-based service options beyond the simple logistics services.

Overall, the relationships amongst the I4 components/technologies and ICT systems outlined above suggest that I4 components/technologies are closely connected with ICT systems. In order to conceptualise these relationships, examples are sought through applications. In this context, Table 6.3 shows a spectrum of technologies, with a brief description of each technology and examples of resources and relevant ICT applications as a link between I4 technology and ICT systems. The information provided in Table 6.3 extends an overview of the core technologies reported earlier (Kang et al., 2016).

4.2. Relationships between Industry 4.0, Circular Economy, and ICT Systems

Recently, de Sousa Jabbour et al. (2018) have proposed a pioneering roadmap to enhance the application of CE principles in organisations by means of I4 approaches. Since CE concepts are defined by a range of process steps (MacArthur, Zumwinkel, and Stuchtey, 2015) focusing broadly on resources and materials from different perspectives (e.g. converting waste material into sources of energy, sharing goods and assets amongst individuals, and using digital manufacturing technologies and various reverse logistics related processes) that are directly connected with a range of I4 technologies, the effective utilisation of those resources can be guaranteed by the best practices of those processes, which are usually run by industry-specific enterprise systems.

Table 6.3: Relationships between I4 Technologies and ICT Systems through Applications and Associated Resources

Technology	Description by Contemporary Research	Examples of Resources	Application of Technology Associated with the Resource(s)	ICT System Associated with the Application
Cyber-physical systems	Enables automation, monitoring, and control of processes and objects in real time (Wang et al., 2015). Provides integration and coordination through embedded devices that are networked to sense, monitor, and actuate physical elements in the real world (Monostori et al., 2016).	Controllers and sensor systems (Wang et al., 2015; Yu et al., 2015). Sensors and actuators especially designed for manufacturing execution systems for energy monitoring (Monostori et al., 2016). Sensor-based communication-enabled autonomous systems and wireless sensor networks (Zhong et al., 2017	3D model-driven remote assembly as a cyber-physical system – an off-site operator can manipulate a physical robot instantly via virtual robot control in a cyber-workspace	Web-based virtual environment, connected through the internet
Cloud manufacturing	Virtual portals which create a shared network of manufacturing resources and capabilities offered as services (Yu et al., 2015)	The internet and communication networks	Suppliers and customers interacting in order to sell and buy services, through the design, simulation, manufacture, and assembly of products (Yu et al., 2015)	Communication technology for connecting through the internet
Internet of Things	A computational system which collects and exchanges data acquired from electronic devices (Kang et al., 2016)	Radio-frequency identification (RFID) technology tags, sensors, barcodes, smart phones (Da Xu et al., 2014)	A number of applications as reported in Da Xu et al. (2014)	Communication technology, such as mobile/wi-fi networks. Database technology of ICT systems for managing real-time data (e.g. enterprise system databases)
Additive manufacturing	Represents agile, connected prototyping of parts of products on a large scale, enabling customisation (Holmstrom et al., 2016)	3D printers	Applications as reported in Guo and Leu (2013)	Communication technology for connection, ICT systems for product prototyping and customisation

Source: Author.

The close relationship between I4, CE, and ICT is further evident from a scientific literature analysis indicating I4 technologies have the potential to leverage the adoption of CE concepts by organisations and society becoming more present in our daily lives (Nobre and Tavares, 2017).

It can be noted from the relationships between CE, Industry 4.0 and sustainable operations, presented using a matrix for measuring the overall experience, that the CE concepts identified by the ReSOLVE framework (MacAuthur, Zumwinkel, and Stuchtey, 2015) are directly related to I4 technologies and reverse logistics. Since the ReSOLVE framework is directly associated with key process steps, which are associated with I4 technologies, these connections are required to be maintained dynamically for real-time data/information flows and the effective performance of CE practices. These connections between processes and technologies can be dynamically maintained through ICT systems. For example, goods (materials) and assets (resources) as part of the sharing aspect of CE concepts can be effective when the information associated with these goods and assets is maintained and shared across the organisation. Enterprise systems within broader ICT systems provide best practices for maintaining data with data integrity, real-time data updates, and sharing across an organisation using data, process, and technical integration.

Similar to the relationship between CE, I4, and ICT outlined above, the processes associated with each step are explored and the relationships identified. Thus, all the relationships identified are presented in Table 6.4.

It can be noted from the above discussion on the key technologies, characteristics, and relationships that ICT plays a significant role in I4R for CE from the perspective of implementation at the firm level. It is also evident from a number of studies on the applications of I4 from both the theoretical and practical perspectives that there is a need for the evaluation of I4R at both the firm and industry levels. Thus, the evaluation of I4R for CE at the firm and industry levels is discussed next, with a framework/tool that can be used to measure readiness at the organisation level, as part of extending it to the industry-specific level.

Table 6.4: Relationships between CE Principles, I4 Components/Technologies and ICT Systems

ReSOLVE Process Step (de Sousa Jabbour et al., 2018)	Industry 4.0 Component Associated with the Process Step	Examples	ICT Systems
Regenerate	Internet of Things (IoT) de Sousa Jabbour et al., 2018)	Conversion of organic waste into sources of energy and raw materials for other chains (de Sousa Jabbour et al., 2018)	Sensors and apps connected through communication networks
Share	IoT and cloud computing (de Sousa Jabbour et al., 2017)	Collecting information on consumers' behaviour for organisations to improve both product and service design for better utilisation or replacement of equipment, and increase customers' satisfaction (Rymaszewska, Helo, and Gunasekaran, 2017)	Websites and apps for connecting people and organisations
Optimise	Cyber-physical systems and IoT (de Sousa Jabbour et al. 2018; Nobre and Tavares, 2017)	Environmental compliance by using RFID tags and IoT, leading to the optimisation of resource usage (de Sousa Jabbour et al. 2018). Case of Philips lighting – with the use of technology, lighting needs can be controlled and monitored online and in real time (Nobre and Tavares, 2017)	RFID tags and sensors connected through communication technologies
Loop	Cyber-physical systems, IoT, and cloud computing (de Sousa Jabbour et al., 2018; Nobre and Tavares, 2017)	Circular model for production and consumption of sports shoes, which allowed the implementation of a re-distributed manufacturing system (Siemieniuch and Sinclair, 2015)	Powered by digital technologies, consumers using a mobile phone app and virtual reality (Siemieniuch et al., 2015)
Virtualise	Cloud computing, IoT, and additive manufacturing technologies (de Sousa Jabbour et al., 2018)	Use virtual reality software to help to resolve issues remotely, thus reducing vehicle travel (Heyes et al., 2018)	Virtualisation software, communication technologies, and web applications (Jain and Paul, 2013)
Exchange	Additive manufacturing (3D printing) (Siemieniuch and Sinclair, 2015; Despeisse et al., 2017)	Advanced renewable and sustainable production, in which the process uses as little material as possible (Siemieniuch and Sinclair, 2015; Despeisse et al., 2017). Use of 3D printing for repair and remanufacturing, production of 3D filament, including the commercialisation of filament that contains recycled materials (Despeisse et al., 2017).	Communication technology for additive manufacturing and IT systems for product design and manufacturing process execution

Source: Author.

5. Framework for Assessing the Critical Role of ICT in Improving I4R for CE

The assessment framework involves two stages: (i) the conceptual framework for assessing the critical role of ICT, based on the framework developed by Ramanathan (2018), by extending the determinants of ICT and data management to the industry/sector level, and (ii) Illustration of the assessment framework for assessing I4R using an industry example (case scenario), identifying measures at the core firm and other organisations in the selected industry.

5.1. Development of the framework for assessing I4R at the firm and industry/sector levels

The proposed framework is based on the conceptual framework for assessing the status of I4R in the manufacturing sector (Ramanathan, 2018). It is assumed that the proposed framework can easily be extended to other sectors by incorporating necessary elements for each determinant.

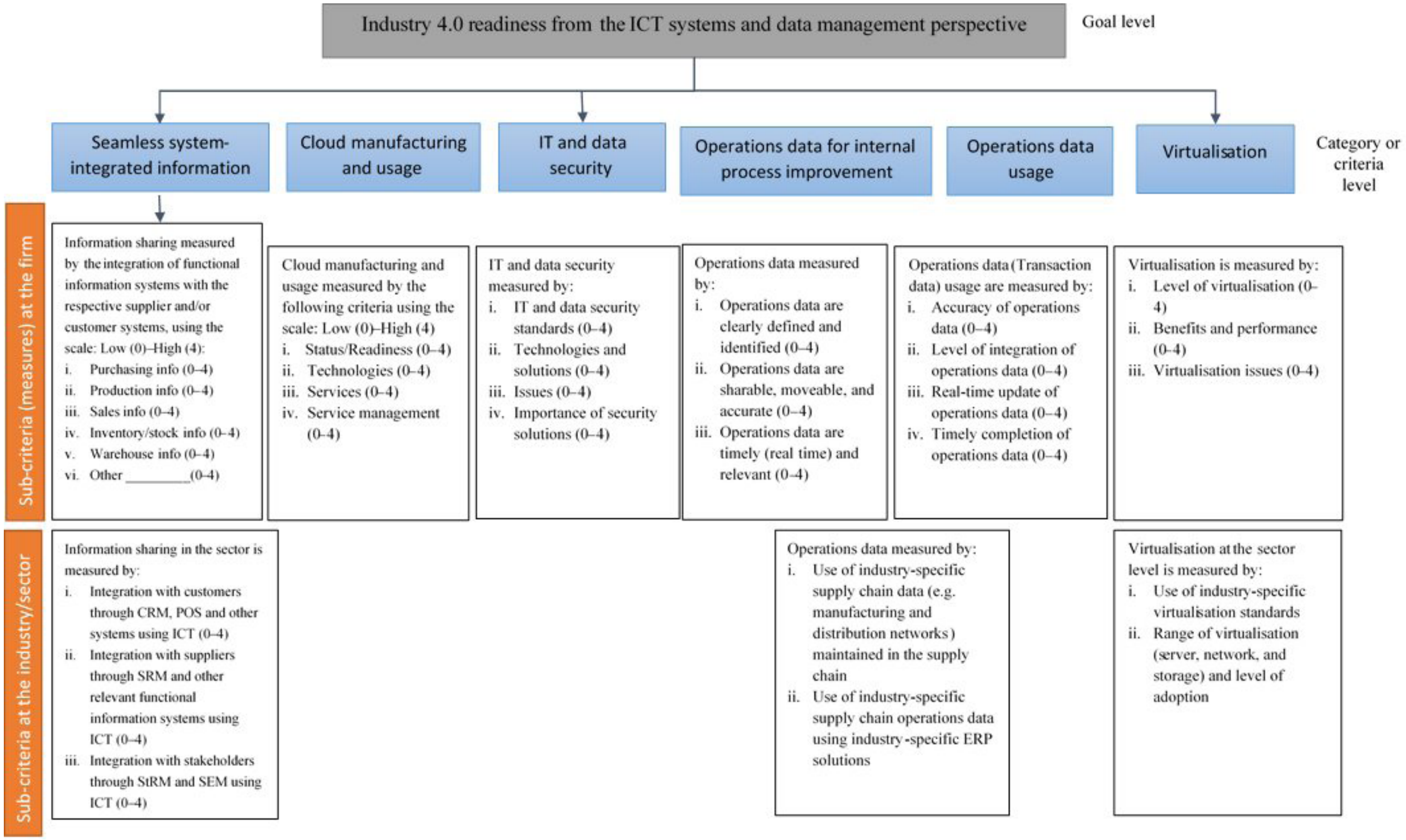
The assessment framework proposed by Ramanathan (2018) consists of two stages: (i) six elements/criteria for rating the level of readiness, mainly focusing on I4, and (ii) one element/criterion, with a CE focus. Based on this framework, in particular the assessment of readiness from the perspectives of ICT systems and data management (determinant 3 of the framework), a hierarchical structure for evaluating I4R at both the firm and industry/sector levels is developed, incorporating details of each criterion at the firm level and sub-criteria (individual measures) at the industry/sector level as shown in Figure 6.1. Each criterion used in this structure is represented by a set of measures at the firm level. However, measures at the industry/sector level are consolidated into three main criteria, since criteria 4 and 5 of determinant 3 (Ramanathan, 2018) related to operational data can be represented by one criterion. In addition, criteria 2 and 3 (cloud usage and IT and data security) measured at the firm level sufficiently represent the industry/sector level perspective. Thus, measures at the industry/sector level are mainly centred around three criteria on information sharing, operational data, and virtualisation. Therefore, the proposed framework is based mainly around three key areas of evaluation at the industry/sector level, in addition to all criteria at the firm level using enterprise systems as a central part of ICT systems at the firm and industry/sector levels. In addition, the hierarchical structure is based on key characteristics of the manufacturing sector, with reference to discrete industries such as the high-tech and automotive industries. Discrete industries within the manufacturing sector can be considered as the centre of I4 initiatives, given the nature of the manufacturing involved and their importance in any global economy, including both developed and emerging economies, such as Thailand and Indonesia.

5.2. Illustration of the framework for assessing I4R using an example from the manufacturing industry/sector

In order to illustrate the proposed framework for assessing I4R for CE, an example of a high-tech industry of the manufacturing sector is considered. For the purpose of illustration, six criteria for assessing I4R from the perspective of ICT systems and data management (determinant 3 of the framework developed by Ramanathan (2018)) are consolidated into four categories: IT-based process integration and cloud usage (cloud-based solutions) for information sharing; IT and data security; operations data collection and usage; and virtualisation. These four categories are closely related to four key elements of ICT systems: (i) IT-based processes, (ii) IT and data security, (iii) operations data including basic data and organisational data (in an enterprise resource planning system, operations data are represented by transactions data and transactions documents), and (iii) virtualisation. It is evident from a broad spectrum of ICT systems that ICT and data security can be directly related to both data and applications, in particular through applications such as cloud-based solutions.

Before presenting the assessment framework using an example of a selected industry case scenario, two key categories (out of four) for the assessment of I4R are outlined, emphasising the relationship between those categories and the level of integration within enterprise systems, since both ICT-based processes and data are integral parts of enterprise systems. The other two categories (ICT and data security, and virtualisation) are discussed later as part of the next stage of this research project.

Figure 6.1: Hierarchical Structure of the Industry 4.0 Readiness Assessment from ICT Perspectives at the Firm and Industry/Sector Levels



ERP = enterprise resource planning , ICT = information and communication technology, IT = information technology

Source: Author.

Level of ICT-based process integration at the firm level, identified by the following parameters:

i. Standard ICT-based processes (no integration of processes to process integration through enterprise systems)

ii. Cross-organisational ICT-based processes (best practices of enterprise systems, from the intention of adding other applications to link with suppliers (SRM), customers (CRM), stakeholders (SEM), to a fully functional enterprise system with all peripheral systems)

iii. Industry-specific business practices (best practices of enterprise systems, combined with industry-specific solutions)

Level of data integration at the firm and sector levels, identified by the following parameters:

i. Data integrity (integrated data; data have the same meaning across multiple functions of the enterprise; unique data set/definitions with no duplicates)

ii. Real-time data at the firm level is available to share with partners in the supply chain – limited to 100% real time

iii. Information sharing through partnership(s) – very limited to full sharing

It can be noted from practices of ICT systems at the firm and industry/sector levels that a range of systems is available to manage ICT, data security, and virtualisation. ICT systems associated with these aspects will be considered at the next stage of the research.

Based on the discussion of sectors and associated industries, and the conceptual framework presented (Figure 6.1), it is clear that a framework for assessing I4R at the industry/sector level needs to collectively assess a range of industries. This can be very challenging when each industry constitutes a range of organisations across the supply chain. In order to make the assessment framework practical and easy to adopt, assessment can be carried out at a level that represents the industry. In this case, each industry can be represented by the supply chain of entities. Thus, the supply chain is considered as the central unit of analysis for assessing I4R at the industry/sector level. In this case, parameters and measures for assessing readiness need to be defined at the firm level, across a range of organisations associated with the supply chain under consideration, specific to the sector.

For example, the high-tech industry in the manufacturing sector will have different supply chain entities and associated parameters/measures to assess I4R at the industry/sector level. Once a reasonable representation of industries within the sector (e.g. manufacturing) is assessed for I4R, they can be used with the appropriate priorities (e.g. weights assigned to each organisation of the selected industry) to determine the overall readiness at the industry/sector level. In order to carry out the assessment of I4R from an ICT perspective for CE for a selected industry/sector, a measurement tool incorporating firm and industry/sector level measures for assessing I4R from the ICT systems perspectives and sustainable practices from CE principles and perspectives is proposed and is shown in Table 6.5. As shown in Table 6.5, measurement is divided into two levels: the firm and industry/sector levels. Each level comprises measurement criteria (only the main criteria) used for assessing I4R from the ICT perspective (Appendix A). In order to make an assessment of I4R from the ICT perspective for a CE, individual organisations selected from each industry/sector as representative organisations of the selected industry need to assess their readiness at the firm and industry/sector levels using the comprehensive assessment criteria outlined in Appendix A. For example, if the selected industry is the high-tech industry, organisations representing the industry could include the manufacturers of high-tech products (central entities of the supply chain of the selected industry), first-tier suppliers, key distributors/wholesalers, and selected retailers. Once each organisation is assessed on their readiness at the firm and industry/sector levels, using Appendix A, Table 6.5 can be completed by assigning the respective I4R assessment from the ICT perspective obtained from the overall assessment (Appendix A) and the additional assessment of I4R from the ICT perspective at the industry/sector level (Appendix B) that corresponds to sustainable practices and CE principles. In this case, each sustainable practice and CE principle can be selected and assigned a percentage (0%–100%) respectively.

Table 6.5: Measures for Assessing Industry 4.0 Readiness from the ICT Systems Perspective for a Circular Economy at the Industry/Sector Level (e.g. High-Tech Industry)

Level of Assessment	Core ICT Systems and Data Management Measures (Appendix A)	Overall Assessment Using Sub-criteria (Appendix A)	Sustainable Practices	Yes (Tick)	Circular Economy Principles	Percentage (0%–100%)
Firm level	i. Seamless system-integrated information using four sub-criteria (0–16) ii. Cloud manufacturing and usage, using four sub-criteria (0–16) iii. IT and data security, using four sub-criteria (0–16) iv. Operations data collection for interal process improvement and operations data usage, using four sub-criteria (0–16) v. Virtualisation, using three sub-criteria (0–12)	______ ______ ______ ______ ______	Sustainable design Sustainable procurement Sustainable manufacturing Sustainable distribution Reverse logistics	☐ ☐ ☐ ☐ ☐	Use of renewable energy Utilisation of digital manufacturing technologies Sharing of resources Virtual systems Renewable materials	______ ______ ______ ______ ______
Industry/ Sector level	i. Seamless system-integrated information sharing across the industry/sector, using three criteria (0–12) ii. Operations data for supply chain improvement across the industry/sector, using two criteria (0–8) iii. Virtualisation across the industry/sector level, using two criteria (0–8)	______ ______ ______	Sustainable design Sustainable manufacturing Sustainable procurement Sustainable distribution Reverse	☐ ☐ ☐ ☐ ☐	Use of renewable energy Utilisation of digital manufacturing technologies Sharing of resources Virtual systems Renewable materials	______ ______ ______ ______ ______
Total score/ rating	Firm level (min: 0, max: 76) Industry/sector level (min: 0, max: 28)	______ ______	Firm level (0%–100%) Industry/sector level (0%–100%)	______ ______	Firm level (0%–100%) Industry/sector level (0%–100%)	______ ______

Source: Author.

In order to illustrate the overall assessment using the framework proposed and outlined above, one industry (i.e. the high-tech industry) is selected with a set of related organisations in the supply chain. It is assumed that the selected industry is represented by six organisations, including the manufacturer of high-tech products, two first-tier suppliers, one wholesaler (main), one logistics service provider, and one retailer (main). Each organisation is assessed at the firm and industry levels for I4R from the ICT systems perspective for a CE using the respective assessment tools (Appendix A and Table 6.5). The summary of the assessment is shown in Table 6.6.

Table 6.6: An Illustrative Example of the High-Tech Industry for I4R for CE from the ICT Systems Perspective

Organisation	I4R from the ICT Perspective at the Firm Level (min: 0, max: 76)	I4R from the ICT Perspective at the Industry/ Sector Level (min:0, max: 28)	Sustainable Practices at the Firm Level (1%–100%)	Sustainable Practices at the Industry/ Sector Level (1%–100%)	Circular Economy Principles at the Firm Level (1%–100%)	Circular Economy Principles at the Industry/ Sector Level (1%–100%)
Manufacturer	70 (92%)	22 (79%)	70%	65%	80%	60%
First-tier supplier 1	72 (95%)	22 (79%)	72%	65%	75%	65%
First-tier supplier 2	68 (89%)	18 (64%)	68%	62%	70%	65%
Wholesaler (main)	66 (87%)	18 (64%)	68%	60%	65%	60%
TPL provider (main)	68 (89%)	20 (71%)	72%	65%	75%	65%
Retailer (main)	65 (86%)	18 (64%)	66%	65%	70%	65%
Overall assessment	409 (90%)	118 (70%)	69%	64%	72.5%	63%

ICT = information and communications technology, TPL = third-party logistics.
Source: Author.

It can be noted from Table 6.6 that there seem to be varying levels of I4R from the ICT system perspective for a CE for the selected industry (high-tech industry) across a range of organisations. Making an overall assessment of I4R for CE requires choosing an appropriate method of assigning appropriate weights for each organisation of the selected industry/sector. If each organisation is assumed with equal weight, the overall assessment of I4R from the ICT perspective at the firm level is shown to be 90%. However, assuming an equal weight for each organisation needs to be justified in the context of assessment. It is suggested that appropriate methods, such as an analytical hierarchical process (AHP) and grey relational analysis (GRA), be used as appropriate and relevant methods for prioritising different entities/organisations of the supply chain of the selected industry for arriving at the overall I4R of the selected industry/sector. The details of these methods are beyond the scope of this chapter and will not be discussed herein. It is expected that the proposed framework for assessing the critical role of ICT in improving I4R be developed as a software tool (online tool) in the future.

6. Trends for Shaping the Future Manufacturing Landscape

Manufacturing is diverse and considered to be a significant part of any economy. Evolving from the traditional manufacturing of the first revolution to the current I4 manufacturing, modern manufacturing is diverse and involves a range of technologies, including CPS, IoT, cloud manufacturing, and additive manufacturing (Hofmann and Rusch, 2017). All of these technologies are closely connected with ICT systems of different forms, and, as a result, manufacturing is no longer limited to traditional processes and resources confined to manufacturing plants (centralised) but is rather distributed in various locations (decentralised), depending on the type of industry and ever-increasing customer expectations, and monitored/controlled by integrated and intelligent manufacturing systems (Chen, 2017). This evolution of manufacturing is driven by various factors and exacerbated by competitive pressures (Kang et al., 2016; Chen, 2017). For example, it is noted from recent studies that I4 technologies are being applied in various industries and there have been cases of shifting of manufacturing from traditional plant to re-distributed manufacturing systems (Nobre and Tavares, 2017).

The future manufacturing landscape can be looked at from a range of perspectives, including the advanced technologies involved, the latest developments from industry perspectives, the level of practices in the world, and factors influencing the future change in manufacturing.

6.1. Future manufacturing landscape from advanced manufacturing technology, application, and industry perspectives

I4, driven by the promise of increased flexibility in manufacturing along with mass customisation, was introduced as the fourth industrial revolution by Germany in 2011. The fundamental change from the previous manufacturing landscape was mainly the adoption of advanced technologies supported by ICT systems for integrated and intelligent manufacturing. Various studies have reported a range of technology-specific assessments of the current practices of I4, highlighting key technology components (Hofmann and Rusch, 2017) and the adoption of those technologies, supported by key characteristics of I4, such as interoperability, integration, intelligence, and capabilities beyond traditional manufacturing (Lu, 2017). The future manufacturing landscape from technologies can be seen as further refinement of all those characteristics and applications in a range of industries. For example, the future of I4 can be the adoption of advanced technologies using integrated and intelligence manufacturing supported by the full interoperability of products, processes, and data using high-speed internet. This means that manufacturing is not only flexible and mass customised, but products are smart and interoperable. In this context, manufacturing using CPS, IoT, and cloud computing can be supported by smart infrastructure for integrated and intelligent manufacturing.

Apart from the shifting manufacturing resources supported by ICT systems and smart infrastructure for mass customisation, another trend in manufacturing is smart factories, comprised of smart logistics, smart grids, smart buildings, and smart products (Kang et al., 2016). For example, smart products can collect and use information from sensor and semantic technologies for continuous process improvement (Mrugalska and Wyrwicka, 2017). In this context, Mrugalska and Wyrwicka (2017) emphasised a future for I4 that allows creating a smart network of machines, products, individuals, and ICT systems in the entire value chain to have an intelligent factory. In addition, the manufacturing execution systems of the future are expected to change from traditional centralised systems to decentralised systems as part of I4's broader vision of an ecosystem of smart factories with intelligent and autonomous shop-floor entities (Almada-Lobo, 2015). Overall, future manufacturing is evolving around smart manufacturing with smart infrastructure and I4's vision of ecosystems of smart factories and smart products as well as decentralised manufacturing systems.

6.2. Future manufacturing landscape from national and international perspectives

As is evident from the broader manufacturing landscape that has evolved from the I4 concept, the concepts have evolved into various forms of advanced manufacturing with different labels. National Network for Manufacturing Innovation and 'Manufacturing USA' by the United States; 'Made in China 2025', introduced in China in 2015; and Japan's Industrial Value Chain Initiative are a few of the initiatives seen in the developed world in recent times (Chen, 2017). All of these initiatives have taken different routes, while I4 has been at the centre of many initiatives in the developing world, aiming for flexible and mass customisation in their manufacturing. Recently, a comprehensive study by Zhong et al. (2017) has reported on current international efforts and identified future directions in each country. In addition to future directions from the global context, Kang et al. (2016) identified global trends in smart manufacturing technology through analysis of the policies and technology roadmaps of Germany, the United States, and the Republic of Korea. They emphasised the need for addressing many issues for the realisation of smart manufacturing, in terms of research, development, and commercialisation. However, there are very limited or no studies that investigate I4 in many other countries, in particular the boom of I4 adoption and/or attempts by developing countries. Amongst many developing countries taking the initiative for I4 adoption, Southeast Asian countries seem to be showing an increased interest in adopting some sort of I4 application across various industries.

7. Guidelines for Policymakers and Decision Makers for Potential Change

From the ICT system perspective, with due consideration of the relationships between I4 technologies and ICT systems, it is important for firm- and industry-level policymakers to consider the evaluation of I4R as a priority and make policies that consider not just the manufacturing landscape but also the ICT landscape of an organisation and industry best practices. It is evident from various research studies (Ramanathan, 2017; Bibby and Dehe, 2018) that firms must begin with understanding their current level of maturity in their specific context if they are to develop their I4 status. In this context, a number of frameworks have been suggested and reported in the literature, including (i) one of the early studies by Blanchet et al., (2014) that classified different European nations into four categories: frontrunners, potentialists, traditionalists, and hesitators; (ii) an assessment of readiness using six levels ranging from outsider (level 0) to top performer (level 5) (Lichtblau, 2015), (iii) the eight dimensions of Yáňez's (2018) maturity framework; and (iv) an assessment tool with six dimensions and four ratings by WMG–University of Warwick (2017). All these assessment frameworks and/or tools indicate the importance of assessing I4R from a range of perspectives. Based on the comprehensive analysis of all these frameworks, Ramanathan (2018) proposed an evaluation of the frameworks using 8 determinants and comprehensive criteria for each determinant (totalling 33 elements) that can be assessed using five levels (0–4). The I4 assessment proposed by Ramanathan (2018) provides an organisation with a final score (with a maximum score of 132 = 33*4) and indicates the status of I4 readiness using four classifications: hesitators (0–33), potentialists (34–66), experienced (67–99), and experts (100–132).

Once the level of maturity in the context of the firm and broader industry level is clear, the organisations need to prioritise improvement opportunities and management development plans (Becker, Knackstedt, and Pöppelbußet, 2009), commence work on developing a blueprint for I4 transition with a clear set of guidelines and steps (Ramanathan, 2018) and seek top-level management support as one of the critical success factors for the successful adoption of I4 (Ramanathan, 2018).

Apart from the need for assessing I4R and prioritising improvement opportunities arising from the level of maturity, organisations need to aware of the critical issues and success factors for I4 adoption. Since the core of I4 is the adoption of advanced/smart technology and organisations already using a range of technologies requiring some changes, one of the most critical issues identified is interoperability (Kang et al., 2016). Other issues that are identified from a range of applications and case studies reported to date include the level of complexity associated with integration and resistance to change from the workforce (Lu, 2017). As is evident from various studies on technology transfer and/or the implementation of new ICT systems, such as enterprise systems, critical success factors also need to be considered as guidelines for moving to I4 transition. In this context, top management support from inception to completion of any I4 transition is critical for a successful outcome. Thus, organisations need to make sure that the critical success factors are identified and sustained during the entire project of I4 transition.

8. Discussion

The investigation into various aspects of the fourth manufacturing revolution, referred to as Industry 4.0 (I4) has been an important subject for many scholars and industry practitioners in recent times. The potential benefits of I4 and the cost of implementation or transition to I4 are well documented, highlighting the need for large capital investment and organisations to be ready for changes expected in the implementation/transition process (Ramanathan, 2016). Since the concept is at an early stage, at least for many emerging economies, studies on I4R have increased in recent times. In this context, I4R for CE is identified as a key driver for many emerging economies as the basis for moving towards I4 with renewed emphasis on sustainable practices.

Although I4 is well established in many developed economies, focusing on circular economies, investigation into I4R for CE is still at an early stage, but limited to the firm level rather than the sector/industry level. This gap is currently being addressed through developing a framework on I4R for CE, through a level of readiness with a set of criteria over a number of determinants (Ramanathan, 2018). One of the determinants considered in the framework is ICT systems and data management, which were explored in this research study.

Recognising the need for readiness at the industry/sector level and the importance of ICT systems for I4R, this chapter outlined an approach to extending the current framework for measuring readiness to cover industry/sector level measures and parameters. Since there are a number of factors that shape this research, including themes of I4 and CE, as well as assessing readiness at the industry/sector level from the perspective of ICT systems, sectors and associated industries are selected from enterprise systems (one of the main IT systems) that closely relate to the respective industry-specific enterprise solutions. These sectors and associated industries are used as the basis for developing the framework using the criteria defined for assessing ICT systems and data management (Ramanathan, 2018).

The framework for assessing readiness, with detailed analysis from the ICT systems perspective, is proposed by incorporating measures and parameters at both the firm and industry/sector levels. The measures and parameters at the firm and industry/sector levels, categorised into five main criteria from the framework by Ramanathan (2018), are guided by ICT systems, such as enterprise systems, given their relevance for the criteria chosen for assessing the ICT systems and data management perspectives. Although measures at the firm level are clear and easy to evaluate using the level of enterprise system applications at the firm level, measures at the industry/sector level are dependent on the applications of advanced ICT systems, such as industry-specific enterprise solutions and advanced enterprise system modules such as SRM, CRM, and SEM.

The framework is illustrated using the example of a manufacturing case scenario (high-tech manufacturing), with relevant parameters and measures at the firm and sector levels. It is expected that a case scenario from the manufacturing sector will be selected for testing and validating the proposed framework for assessing the critical role of ICT in improving I4R for CE from the ICT systems perspective in the near future. Once the case organisation is selected, plans for data collection will be finalised, followed by the required data collection, case scenario analysis, and reporting of the results and findings.

It is evident from the trends in the future manufacturing landscape that manufacturing is rapidly moving from traditional, centralised plant-based manufacturing to a re-distributed, decentralised system of manufacturing. In addition, manufacturing is moving towards adopting the concepts of CE, supported by smart infrastructure and logistics amongst many other contemporary practices. In order for ASEAN policymakers and businesses to prepare for this change in the manufacturing landscape in the future, directions and guidelines are proposed, highlighting the need for assessing I4R for CE, prioritising the improvement opportunities, and recognising the importance of the critical role ICT plays at the firm and industry levels.

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Appendix A: Framework for Assessing Industry 4.0 Readiness from the ICT Systems Perspective at the Firm Level

This framework is based on one of the criteria developed for assessing the status of Industry 4.0 readiness (I4R) in manufacturing (Ramanathan, 2018) and succinct literature on broader information and communications technology (ICT) systems and associated technologies. This framework is directly related to the hierarchical structure of I4R from the ICT perspective at the firm and industry/sector levels (Figure 6.1) and, therefore, can only be used in conjunction with specific parameters of the manufacturing organisation of the selected industry. This is ideally carried out using piloting of the framework using case studies.

Sub-criteria for Assessing Seamless System-integrated Information	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Criterion 1: Seamless System-integrated Information					
Purchasing information system (PIS) within an enterprise resource planning (ERP) system across the enterprise, integrated with Industry 4.0 technologies using ICT	There is no PIS. Relevant purchasing data and information are stored and processed manually using simple applications, which are not integrated with other applications/ systems.	PIS is of interest at the purchasing department level but is not explicitly incorporated into an enterprise-level procurement strategy, such as centralised purchasing.	PIS is recognised as important and is being introduced as a standalone system (e.g. not part of an ERP system) and is incorporated into the strategy formulation process.	PIS of the ERP system has been developed and/ or bought and implementation is in progress in stages. However, PIS is not directly integrated with relevant suppliers' systems using ICT and relevant technologies.	PIS of the ERP system has been implemented and is being continuously reviewed and updated. PIS is directly integrated with relevant suppliers' systems using ICT and associated technologies, including RFID and sensors.
Production information system (PrIS) within an ERP system across the enterprise, integrated with Industry 4.0 technologies using ICT	There is no PrIS. Production-relevant data and information are stored and processed manually using simple applications, which are not integrated with other applications/ systems.	PrIS is of interest at the production department level but is not explicitly incorporated into an enterprise-level production planning strategy, such as sales and operations planning.	PrIS is recognised as important and is being introduced as a standalone system (e.g. not part of an ERP system) and is incorporated into the strategy formulation process.	PrIS of the ERP system has been developed and/ or bought and implementation is in progress in stages. However, PrIS is not directly integrated with suppliers and customers using ICT, including RFID and sensors.	PrIS of the ERP system has been implemented and is being continuously reviewed and updated. PrIS is directly integrated with suppliers and customers using ICT and associated technologies, including RFID and sensors.

Sub-criteria for Assessing Seamless System-integrated Information	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Sales information system (SIS) within an ERP system across the enterprise, integrated with Industry 4.0 technologies using ICT	There is no SIS. Sales-relevant data and information are stored and processed manually using simple applications, which are not integrated with other applications/ systems.	SIS is of interest at the sales department level but is not explicitly incorporated into an enterprise-level sales and distribution strategy.	SIS is recognised as important and is being introduced as a standalone system (e.g. not part of an ERP system) and is incorporated into the strategy formulation process.	SIS of the ERP system has been developed and/ or bought and implementation is in progress in stages. However, SIS is not directly integrated with customers using ICT and relevant technologies.	SIS of the ERP system has been implemented and is being continuously reviewed and updated. SIS is integrated with customers using ICT and associated technologies.
Inventory/warehouse information system (IWIS), within an ERP system across the enterprise, integrated with Industry 4.0 technologies, using ICT	There is no IWIS. Inventory and warehouse-relevant data and information are stored and processed manually using simple applications, which are not integrated with other applications/ systems.	IWIS is of interest at the relevant functional level but is not explicitly incorporated into an enterprise-level inventory/ warehouse management strategy.	SIS is recognised as important and is being introduced as a standalone system (e.g. not part of an ERP system) and is incorporated into the strategy formulation process.	IWIS of ERP system has been developed and/ or bought and implementation is in progress in stages. However, IWIS is not directly integrated with internal/external customers using ICT and relevant technologies.	IWIS of ERP system has been implemented and is being continuously reviewed and updated. IWIS is integrated with customers using ICT and associated technologies (e.g. RFID and automated guided vehicles).
Criterion 2: Cloud Manufacturing and Usage (Ramanathan, 2018)					
Manufacturing infrastructure – current status and readiness	Not suitable for a cloud manufacturing environment and/ or no interest in integration of distributed manufacturing resources or applications.	There is some interest in cloud manufacturing infrastructure but will need substantial overhaul for cloud manufacturing infrastructure readiness.	Current infrastructure is ready for cloud manufacturing and Some of the plant, equipment, and systems can be upgraded for cloud manufacturing.	Current infrastructure is ready for cloud manufacturing and most of the plant, equipment, and systems meet cloud manufacturing requirements and standards.	Current infrastructure is ready and all the plants, equipment, and systems meet cloud manufacturing requirements and standards.
Key enabling cloud manufacturing technologies	Current machines and systems cannot be integrated with cloud manufacturing technologies through the internet.	Some machines/ equipment and systems can be integrated with cloud manufacturing technologies through ICT systems, but there is no ERP system for functional applications and no machine-to-machine (M2M) connectivity.	Most machines/ equipment and systems can be integrated with cloud manufacturing technologies and some machines can be controlled through ICT systems and have M2M connectivity.	All machinery/ equipment can be controlled through ICT systems and most machines/ equipment have M2M connectivity.	All machinery/ equipment can be completely controlled through ICT systems and have full M2M capability.

Sub-criteria for Assessing Seamless System-integrated Information	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Cloud manufacturing services (e.g. virtualising manufacturing resources and capabilities, manufacturing as a service and multi-tenancy, intelligent on-demand manufacturing, flexibility and scalability)	No cloud manufacturing service in use and no consideration of manufacturing cloud.	No cloud manufacturing service in use, but business cases for their adoption are being prepared for consideration.	Cloud manufacturing architecture and some of the cloud manufacturing services are being planned/ piloted.	Some cloud manufacturing services are in use.	Cloud manufacturing services are widely adopted with continuous improvements being made in their use.
Cloud manufacturing service management	No effective management and coordination of cloud services in a centralised way to ensure the service performance, quality, security and successful operation of manufacturing clouds.	Management and coordination of cloud services only for a limited scope (e.g. only in some functional areas) and provided in a decentralised way.	Management and coordination of cloud services for a majority of functional areas of the enterprise, but provided in a decentralised way.	Management and coordination of cloud services for all of functional areas of the enterprise, but provided in a decentralised way.	Fully effective management and coordination of cloud services in a centralised way to ensure the service performance, quality, security, and successful operation of manufacturing clouds.
Criterion 3: IT and Data Security					
IT and data security standards	Not recognised as an important aspect for the organisation.	IT and data security standards are recognised as important and security standards are being considered for adoption.	IT and data security standards (Chen and Zhao, 2012) have been adhered in multiple areas of the organisation.	IT and data security standards have been achieved across the entire organisation and are constantly monitored and upgraded with the latest updates on improvement.	IT and data security standards have been achieved across the entire organisation and have been extended to cover applications of direct customers and suppliers.

Sub-criteria for Assessing Seamless System-integrated Information	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Criterion 3: IT and Data Security					
IT and data security technologies and solutions	Not a concern for the organisation.	IT and data security technologies and solutions are recognised as important and are being considered for adoption.	IT and data security solutions have been implemented in multiple areas of the business.	IT and data security solutions have been comprehensively implemented across the business and are constantly monitored for bridging gaps that arise with time.	IT and data security solutions, with continuous upgrading, have been comprehensively implemented across the business and have been extended to cover data and information sharing with all relevant external partners.
IT and data security issues	Not a concern at this stage and/or not recognised/ identified as an issue.	IT and data security as an important issue is recognised and preliminary steps have been taken for addressing the issue.	IT and data security is continuously addressed across multiple areas of the business.	Security issues have been addressed across the enterprise.	Security issues have been addressed across the enterprise and extended to include any security concerns from customers and suppliers.
Importance of IT and data security	Very low	Low	Neutral	High	Very high
Criterion 4: Operations Data Collection for Internal Process Improvement and Operations Data Usage					
Enterprise-level organisational and master data	No unique data definitions for enterprise-wide data and no single database for maintaining master data.	Unique data across the enterprise but no single database for enterprise-wide data	Unique data definitions and single database for most enterprise-wide data	Unique data definitions, single database for enterprise-wide data using an enterprise resource planning (ERP) system, but limited functional applications are being used.	Unique data definitions, single database for enterprise-wide data using an ERP system with full ERP system functionality.

Sub-criteria for Assessing Seamless System-integrated Information	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Criterion 4: Operations Data Collection for Internal Process Improvement and Operations Data Usage					
Enterprise-wide transactional (operations) data	No formal data collection system. Data are collected manually by departments for their own usage as needed.	Required data is collected digitally (e.g. financial/ accounting data by 'mind your own business' systems) by some departments and data available are current.	Data is collected digitally by most departments using the relevant functional applications of the ERP system.	Comprehensive and automated structure across the enterprise for digital data collection. Arrangements in place to acquire and share data digitally with some important supply chain partners.	Comprehensive and automated structure across the enterprise and with all key supply chain partners to acquire and share data digitally, using ERP integrated with other systems, such as SCM, CRM, and strategic enterprise management system (SEM).
Enterprise-wide information and reporting	No formal enterprise-wide information and reporting.	Information is collected and processed by some departments.	Information is collected and processed by all departments but with limited reporting.	Information is collected and processed by all departments, and makes standard and flexible analyses using ERP system and user defined structures.	Information is collected and processed by all departments from a variety of sources (e.g. internal ERP system, business warehouse, external data, other systems such as SCM and CRM) for business intelligence and data analytics.
Enterprise-wide operations data usage, quality and, accuracy	Operations data are collected manually but not evaluated for accuracy and quality.	Operations data are collected manually. Some considerations are given for evaluating the quality and accuracy.	Operations data are collected across the enterprise using standalone systems but with limited evaluation on quality and accuracy.	Comprehensive operations data across the enterprise, collected using an enterprise-wide ERP system and are evaluated for accuracy and quality.	Comprehensive operations data across the enterprise are collected using an enterprise-wide ERP system and are of high quality, timely, and accurate. Operations data are used for decision making.

Sub-criteria for Assessing Seamless System-integrated Information	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Criterion 5: Virtualisation					
Virtualisation at system, storage, and network levels	There is awareness but no plans to develop the capacity.	Some virtualisation of resources (e.g. hardware, storage, network) are being planned	Some virtualisation of resources (e.g. hardware, storage, network) have been implemented.	Comprehensive use of virtualisation across the entire organisation but limited to traditional resources, not associated with Industry 4.0 resources.	Complete virtualisation of hardware, operations systems, applications, storage, and networks through cyber-physical production systems.
Virtualisation benefits and performance (e.g. flexibility, availability, scalability, hardware utilisation, security, cost and load balancing)	Aware of benefits but no plans to develop the capacity.	Some plans to develop capacity and expected to have some benefits in the future.	Some benefits as a result of some virtualisation.	Significant benefits and advantages are currently being achieved.	Full benefits are achieved as a result of virtualisation.
Virtualisation issues	Not a concern at this stage or issues are not being identified/ addressed.	Issues are identified and preliminary steps have been taken for addressing the issues.	Issues are continuously identified and addressed across multiple areas of the business.	All issues have been addressed across the enterprise.	All issues have been addressed across the enterprise and extended to include any security concerns from customers and suppliers.

Appendix B: Framework for Assessing Industry 4.0 Readiness from the ICT Systems Perspective at the Industry/Sector Level

This framework is directly related to the framework for assessing Industry 4.0 readiness (I4R) from the information and communications technology (ICT) perspective at the firm level (Appendix A) and therefore should only be used in conjunction with the assessment of I4R from the ICT systems perspective at the firm level of selected organisations (e.g. manufacturers, first and second tier suppliers, third-party logistics service providers, and wholesalers/distributors and retailers) of the selected industry/sector, taking into consideration the specific parameters of the manufacturing organisation of the selected industry. While individual case studies can provide I4R from the ICT perspective at the firm level, I4R from the ICT perspective at the industry/sector level requires case studies associated with the key organisations of the selected industry/sector. For example, I4R from the ICT perspective for the automotive industry requires assessment of the core manufacturing organisation, upstream suppliers (e.g. engine suppliers and body/frame suppliers) and downstream customers (wholesalers, exporters, and dealers). .

Sub-criteria for Assessing Seamless System-integrated Information Sharing	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Criterion 1: Seamless System-integrated Information Sharing across the Industry/Sector					
Information sharing through system integration with customers, using customer relationship management (CRM) and information systems (e.g. point of sales (POS), maintenance monitoring, stock/ inventory)	Not suitable for information sharing with customers and/ or no interest in a CRM system and integration with customers' systems for information sharing.	There is some interest in information sharing with customers, interest in an CRM system, and integration with customers' systems for information sharing, but not explicitly incorporated into corporate strategy.	Information sharing with customers, deploying a CRM system and integration with customers' system/s are being introduced.	Information sharing with customers has been introduced and implementation of a CRM system and integration with customers' systems are in progress in stages.	Information sharing with all/relevant customers is in full operation, using a CRM system and integration with customers' systems. Information sharing capabilities are continuously monitored, reviewed, and updated.

Sub-criteria for Assessing Seamless System-integrated Information Sharing	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Information sharing through system integration with suppliers, using a supplier relationship management (SRM) system and relevant information systems (stock/inventory overview, production information)	Not suitable for information sharing with suppliers and/ or no interest in an SRM system and integration with suppliers' systems for information sharing.	There is some interest in information sharing with suppliers, interest in an SRM system and integration with suppliers' systems for information sharing, but not explicitly incorporated into corporate strategy.	Information sharing with suppliers, deploying an SRM system, and integration with customers' system/s are being introduced.	Information sharing with suppliers has been introduced. Implementation of an SRM system and integration with customers' systems are in progress in stages.	Information sharing with all/relevant suppliers is in full operation, using an SRM system and integration with suppliers' systems. Information sharing capabilities are continuously monitored, reviewed, and updated.
Information sharing through system integration with stakeholders, using stakeholder relationship management (StRM) and/or strategic enterprise management (SEM) systems	No interest in an StRM/ SEM system, and sharing information with stakeholders.	There is some interest in information sharing with stakeholders, no interest in an StRM/SEM system and integration with stakeholders' systems for information sharing, but not explicitly incorporated into corporate strategy.	Information sharing with stakeholders, deploying an StRM/SEM system and integration with stakeholders' system/s are being introduced.	Information sharing with stakeholders has been introduced. Implementation of an StRM/ SEM system and integration with stakeholders' systems are in progress in stages.	Information sharing with all/relevant stakeholders is in full operation, using an StRM/ SEM system and integration with stakeholders' systems. Information sharing capabilities are continuously monitored, reviewed, and updated.
Criterion 2: Operations Data for Supply Chain Improvement across the Industry/Sector					
Industry/sector specific supply chain data (e.g. manufacturing network of plants, suppliers, distribution network of warehouses, customers)	No unique data definitions for industry-specific supply chain data and no integration of supply chain data with enterprise-wide data.	Unique data definitions for industry-specific supply chain data, but no integration of supply chain data with enterprise-wide data.	Unique data definitions for industry-specific supply chain data, and there is limited integration of supply chain data with enterprise-wide data, using industry-specific ERP solutions.	Unique data definitions, integrated databases for enterprise-wide and supply chain data, using some integration of an ERP system and industry solution at the organisation level.	Unique data definitions, integrated databases for enterprise-wide and supply chain data, using full integration of an ERP system and industry solution at organisation level.

Sub-criteria for Assessing Seamless System-integrated Information Sharing	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Criterion 2: Operations Data for Supply Chain Improvement across the Industry/Sector					
Industry/sector specific supply chain operations data (e.g. cross-plant production orders, multi-supplier purchase orders), using specific supply chain data, maintained in industry-specific ERP solutions	No formal data collection system for supply chain-specific data. Supply chain-specific operations data are collected manually by departments for their own usage as needed.	Required supply chain data are maintained/ collected digitally (e.g. financial/ accounting data by MYOB system) by some departments, and supply chain operations data available are current.	Supply chain operations data is collected digitally by most departments using relevant functional applications of the ERP system, but no integration with industry-specific solutions.	Comprehensive and automated structure across the enterprise for digital supply chain operations data collection. Arrangements in place to acquire and share supply chain operations data digitally with some important supply chain partners, using industry solutions.	Comprehensive and automated structure across the enterprise and with all key supply chain partners to acquire and share supply chain operations data digitally, using ERP integrated with other systems, such as SRM, CRM and StRM systems.
Criterion 3: Virtualisation across the Industry/Sector Level					
Industry-specific virtualisation standards	Not recognised as an important aspect for the organisation.	Industry-specific standards are recognised as important and are being considered for adoption.	Industry-specific standards have been adhered to in multiple areas of the organisation.	Industry-specific standards have been achieved across the entire organisation and are constantly monitored and upgraded with the latest updates on improvement.	Industry-specific standards have been achieved across the entire organisation and have been extended to cover applications of direct customers and suppliers.
Virtualisation at the system, storage, and network levels, and level of adoption (full, hardware layer, operating system-layer, server, application, resource, and storage virtualisation)	There is awareness but no plans to develop the capacity at the organisation level and no consideration of industry-specific virtualisation solutions.	Some virtualisation of resources (e.g. hardware, storage, network) are being planned at the organisational level, but no consideration of industry-specific solutions.	Some virtualisation of resources (e.g. hardware, storage, network) has been implemented and is not associated with industry standards.	Comprehensive use of virtualisation across the entire organisation, but limited to traditional resources, not associated with industry standards.	Complete virtualisation through cyber-physical production systems complete with the use of a digital twin (computerised duplication of physical assets that enables simulation and testing to be carried out prior to actual operations).