Chapter 3

Industry 4.0 Readiness with a Circular Economy Focus: An Integrated Assessment Framework

Krishnamurthy Ramanathan

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CHAPTER 3

Industry 4.0 Readiness with a Circular Economy Focus: An Integrated Assessment Framework

Krishnamurthy Ramanathan

1. The Importance of Firm-level Industry 4.0 Readiness from a Circular Economy Perspective

Industry 4.0 is talked about extensively as the 'Fourth Industrial Revolution' that will have a major impact on manufacturing value-chains at both local and global levels, not just in industrially advanced high-cost nations but also in less industrialised low-cost nations (Schwab, 2016). While many descriptions and definitions of Industry 4.0 exist, a simple way of looking at it at an overall level is as a 'collective term for technologies and concepts of value-chain organization' (Hermann, Pentek, and Otto, 2015).

According to the Rüßmann et al. (2015) of the Boston Consulting Group, this transformation is being driven by several foundational technological advances that enable sensors, machines, workpieces, and information technology (IT) systems to be linked along a value chain beyond a single enterprise. Deloitte (2015) refers to these foundational technological advances as 'acceleration through exponential technologies'. While the broad Industry 4.0 literature (Albert, 2015; D'Aveni, 2015; Deloitte, 2015; Hermann, Pentek, and Otto, 2015; Iansiti and Lakhani, 2014; Mohr and Khan, 2015; Whitmore, Agarwal, and Xu, 2015) classifies these exponential technologies in many ways, they include the industrial Internet of things (IoT), big data and analytics, simulation, advanced robotics, artificial intelligence (AI), additive manufacturing (3D printing), cloud-based software platforms, and augmented reality.

Deloitte (2015), in their study of challenges and solutions for the digital transformation and use of exponential technologies, pointed out that Industry 4.0 has four main characteristics, namely: vertical networking of smart production systems through the use of cyber-physical production systems (CPPS); horizontal integration of real-time optimised global value-creation networks; cross-disciplinary through-engineering across the entire value chain and across the full life-cycle of both products and customers; and the acceleration of individualised solutions, flexibility, and cost savings in industrial processes through the use of exponential technologies. Hermann, Pentek, and Otto (2015) pointed out that an Industry 4.0 scenario needs to take into consideration six design principles – interoperability, virtualisation, decentralisation, real-time capability, service orientation, and modularity.

However, Ubisense, a global firm specialising in location intelligence solutions found out, through its 2014 Smart Manufacturing Technologies Survey of 252 manufacturing engineers and product designers, that 40% of manufacturers have no visibility into the real-time status of their manufacturing processes; more than 80% rely on human observation to support process-improvement initiatives; nearly 85% of quality issues can be attributed to worker errors; nearly 10% of manufacturing personnel spent considerable time daily looking for equipment and products; and that over 10% of cycle time per product is non-value-added time (Ubisense, 2015). This suggests that even in industrially advanced settings, there are many barriers to Industry 4.0 that need to be overcome by firms in the manufacturing sector.

Schumacher, Erol, and Sihn (2016), based on the findings of strategic orientation workshops with various companies, pointed out that transitioning to Industry 4.0 presents many difficulties to firms and that the following are the major issues:

- Inability to determine their state of development with regard to an Industry 4.0 vision, thereby making it difficult for them to identify specific steps that need to be taken in terms of actions, projects, and programmes; and
- Inability to link their specific domain and business strategy.

Schumacher, Erol, and Sign (2016) thus argued that to overcome uncertainty and dissatisfaction in manufacturing firms in adopting Industry 4.0, methods and tools have to be developed to provide them with the needed guidance to plan the transition and align business strategies and operations.

The first objective of this chapter is therefore to develop a conceptual framework that will enable a firm in the manufacturing sector to assess its Industry 4.0 readiness (I4R). In recent years, several attempts have been made to develop I4R frameworks, and these have been popularly referred to as 'maturity models' or 'readiness models'. This study will, therefore, adopt an eclectic approach to develop the I4R assessment framework by evaluating the concepts and ideas proposed by existing models and incorporating them into a holistic framework.

Secondly, this chapter will also focus on developing a framework that will enable a firm in the manufacturing sector to assess its I4R from a circular economy (CE) perspective. The positive impact that Industry 4.0 can have from a CE perspective is that it can, if well designed and used effectively, help to minimise the leakage of both biological and technical materials, especially the loss of materials, energy, and labour (Nguyen, Stuchtey, and Zils, 2014). However, this second objective is based on the premise that rather than seeing less leakage of biological and technical materials as a by-product of Industry 4.0 adoption, it would be more advantageous if firms explicitly build in CE considerations into their Industry 4.0 actions, projects, and programmes.

To achieve these two objectives this chapter will adopt the following steps:

- Develop a framework for assessing the status of I4R in a manufacturing firm;
- Develop a framework for assessing the extent of the CE focus in I4R;
- Propose a classification to determine the extent to which a manufacturing firm's Industry 4.0 status has a CE focus. This will be referred to as a 'Circular Economy-focused Industry 4.0 Readiness Rating' (CEF I4R Rating); and
- Delineate some managerial implications, from a CE perspective, for manufacturing firms that are transitioning to an Industry 4.0 setting.

The rest of this chapter is presented in four sections. The next, which is the second, presents the framework for assessing the status of I4R in a manufacturing firm. The third section proposes an approach to evaluate the extent of the CE focus in I4R. The next examines how management in a manufacturing firm can combine the findings to evaluate where they stand in terms of the CE focus of their I4 operations ecosystem. The last section delineates some managerial implications and presents some concluding remarks.

2. Assessing the Status of Industry 4.0 Readiness at the Firm Level

One of the earliest studies on I4R is due to RolandBerger (2014). This study examined Industry 4.0 readiness in Europe and highlighted the challenges faced not just at the firm level but within the business eco-system and the national economic setting. Based on this analysis, the report suggested that different European nations could be classified as 'frontrunners', 'potentialists', 'traditionalists', and 'hesitators' with respect to transitioning to Industry 4.0. Clearly, the initiatives to be taken by the nations in each category to advance to Industry 4.0 would be different. Frontrunner nations, such as Germany and Sweden, would set the pace, while hesitator nations would have much to do to make the transition. However, this report is not a firm-level study and it also does not present the methodology used to make the national-level assessments.

The IMPULS–Industrie 4.0 Readiness study by Lichtblau et al. (2015) proposed six dimensions, namely: 'strategy and organisation', 'smart factory', 'smart operations', smart products', 'data-driven services', and 'employees.' Each of these core dimensions contained several sub-dimensions to enable a comprehensive evaluation of I4R with respect to each of these dimensions. Table 3.1 shows these details. Six rating levels are used in conjunction with these determinants to assess the state of I4R. These levels are: level 0, outsider; level 1, beginner; level 2, intermediate; level 3, experienced; level 4, expert; and level 5, top performer. While insightful to experienced practitioners, this approach is not easy for a firm to use as a self-assessment tool.

The WMG–University of Warwick I4R (2017) assessment tool, also has six dimensions, namely: 'strategy and organisation', 'manufacturing and operations', 'supply chain', 'products and services', 'business model' and 'legal considerations.' Table 3.1 shows these dimensions and the associated sub-dimensions. Four rating levels are used in conjunction with these determinants to assess the state of I4R. These levels are: level 1, beginner; level 2, intermediate; level 3, experienced; and level 4, expert. The advantage of the WMG I4R tool is that it can be used as a self-assessment tool by firms.

While the 'manufacturing and operations' dimension is comprehensive and insightful from a manufacturing technology perspective, other aspects, such as quality and energy consumption, are not explicitly included. Also, the people dimension has not been adequately addressed.

The Yáňez (2018) Maturity Index Framework has eight dimensions, namely: 'operational processes', 'industrial assets', 'energy', 'people', 'internal logistics and supply chain', 'quality', 'supply-demand synchronisation', and 'time to market'. These dimensions and their sub-dimensions are shown in Table 3.1. This framework, while very useful for assessing I4R from the manufacturing and operations perspective, does not explicitly address equally important dimensions, such as 'strategy and organisation', and 'information technology systems.'

The Akdil, Ustungdag, and Cevikcan (2018) Maturity and Readiness Model for Industry 4.0, proposes 10 core dimensions. These are: 'smart products and services', 'smart business processes: production, logistics, and procurement', 'smart business processes: R&D and product development', 'smart business processes: after-sales service', 'smart business processes: human resources', 'smart business processes: pricing/promotion', 'smart business processes: sales and distribution channels', 'smart business processes: information technology', 'smart business processes: smart finance', and 'strategy and organisation'. Table 3.1 shows these dimensions, the sub-dimensions, and principles to be used to assess I4R. The authors use four stages, namely 'absence,' 'existence,' 'survival', and 'maturity', to determine the maturity level. While insightful to experienced practitioners, this approach is not easy for a firm to use as a self-assessment tool.

Table 3.1: Summary of Core Dimensions and Sub-dimensions of Selected Industry 4.0 Readiness Assessment Frameworks

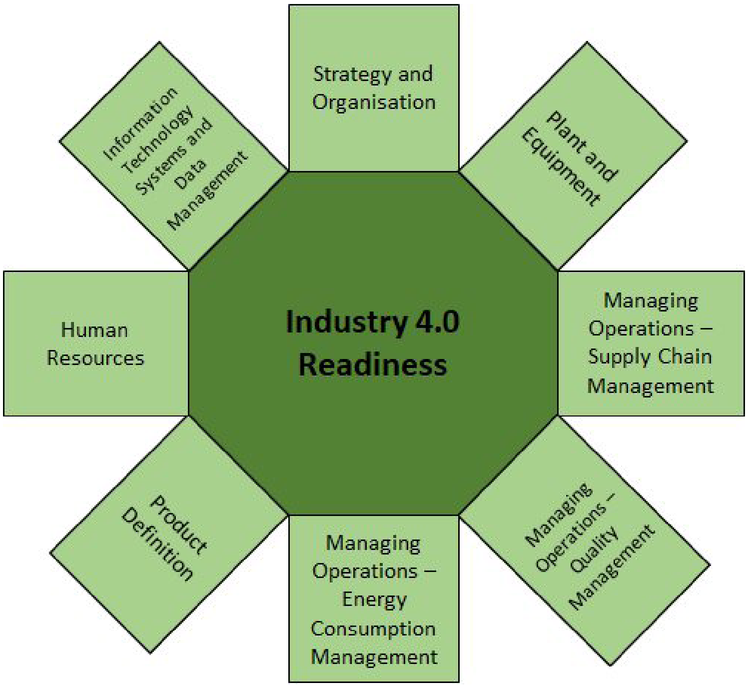
IMPULS–Industrie 4.0 Readiness Framework (2015)	WMG–University of Warwick Industry 4.0 Readiness Assessment Tool (2017)	Yanez Maturity Index Framework (2018)	Akdil, Ustungdag, and Cevikcan Maturity and Readiness Model for Industry 4.0 (2018)
Strategy and Organisation • Strategy • Investments • Innovation management Smart Factory • Digital modelling • Equipment infrastructure • Data usage • Information technology (IT) Systems Smart Operations • Cloud usage • IT security • Autonomous processes • Information sharing Smart Products • Data analytics in the usage phase • Add-on functionalities Data-driven Services • Share of data used • Share of revenues • Data-driven services Employees • Staff acquisition • Employee skill set	Strategy and Organisation • Degree of strategy implementation • Measurement • Investments • People capabilities • Collaboration • Leadership • Finance Manufacturing and Operations • Automation • Machine and operations system integration • Equipment readiness for I4 • Autonomously guided workpieces • Self-optimising processes • Digital modelling • Operations data collection • Operations data usage • Cloud solution usage • IT and data security Supply Chain • Inventory control using real-time data management • Supply chain integration • Supply chain visibility • Supply chain flexibility • Lead times	Operational Processes • Sensoring, monitoring, and control • Intelligent processes • Virtualisation Industrial Assets • Flexible manufacturing and modular systems • Access and remote control • Predictive maintenance Energy • Monitoring and control • Smart consumer • Efficient energy systems People • Digital training • Interfaces • Human-cyber-physical Systems Internal Logistics and Supply Chain • Warehouse management • Internal logistics • Manufacturing supply Quality • Unitary quality control • Digital quality management • Full traceability in value chain	Smart Products and Services • Real-time data management • Interoperability • Decentralised • Service oriented Smart Business Processes: Production, Logistics, and Procurement • Real-time data management • Virtualisation • Decentralised • Agility • Integrated business process Smart Business Processes: R&D and Product Development • Real-time data management • Virtualisation • Agility Smart Business Processes: After-sales Service • Real-time data management • Virtualisation • Agility • Service oriented Smart Business Processes: Human Resources • Real-time data management • Agility

Table 3.1: (Continuted) Summary of Core Dimensions and Sub-dimensions of Selected Industry 4.0 Readiness Assessment Frameworks

IMPULS–Industrie 4.0 Readiness Framework (2015)	WMG–University of Warwick Industry 4.0 Readiness Assessment Tool (2017)	Yanez Maturity Index Framework (2018)	Akdil, Ustungdag, and Cevikcan Maturity and Readiness Model for Industry 4.0 (2018)
	Products and Services • Product customisation • Digital features of products • Data-driven services • Level of product data usage • Share of revenue Business Model • 'As a service' business model • Data-driven decisions • Real-time tracking • Real-time and automated scheduling • Integrated marketing channels • IT-supported business Legal Considerations • Contracting models • Risk • Data protection • Intellectual property	Supply-Demand Synchronisation • Product tailored to customer based on data • Customer logistics • Logistic routes Time to Market • Innovation process • Product life cycle	Smart Business Processes: Pricing/Promotion • Real-time data management • Decentralised • Service oriented • Integrated business process Smart Business Processes: Sales and Distribution Channels • Real-time data management • Agility • Service Oriented Smart Business Processes: Information Technology • Real-time data management • Interoperability • Virtualisation Smart Business Processes: Smart Finance • Real-time data management • Decentralised Strategy and Organisation • Business models • Strategic partnerships • Technology investments • Organisational structure and leadership

Based on the four frameworks described in Table 3.1 and an evaluation of other publications related to specific aspects of Industry 4.0, an eclectic framework consisting of eight key determinants is proposed for assessing I4R at the firm level. These eight determinants are listed below and are shown schematically in Figure 3.1.

Figure 3.1: Schematic Representation of the Determinants of Industry 4.0 Readiness



Source: Author.

The eight determinants of the proposed I4R framework are:

- Strategy and organisation
- Plant and equipment
- Information technology systems and data management
- Human resources
- Product definition
- Managing operations – energy consumption management

- Managing operations – quality management
- Managing operations – supply chain management

Each of these determinants consists of several elements, which, collectively, will determine the Industry 4.0 readiness level with respect to each determinant. These elements are shown in Appendix 1, titled 'A Framework for Assessing the Status of Industry 4.0 Readiness in Manufacturing'. The elements for each of these determinants were synthesised from the four models described in Table 3.1. Furthermore, the elements for the determinants were also obtained from sources that dealt specifically with individual determinants of relevance to I4R. These are summarised in Table 3.2 below.

Table 3.2: Sources Used in Developing the Elements of the Proposed Framework for Assessing I4R

Determinant	Sources
Strategy and organisation	Akdil, Ustundag, and Cevikcan (2018), Lichtblau et al. (2016), WMG–University of Warwick (2017), Yáňez (2018)
Plant and equipment	Akdil, Ustundag, and Cevikcan (2018), Kolberg and Zühlke (2015), Lichtblau et al. (2016), Stock and Seliger (2016), Wagner, Herrmann, and Thiede (2017), WMG–University of Warwick (2017), Yáňez (2018)
Information technology systems and data management	Akdil, Ustundag, and Cevikcan (2018), Li, Xu, and Zhao (2015), Li, Tryfonas, and Li (2014), Lichtblau et al. (2016), Luo et al. (2016), Weber et al. (2017), WMG–University of Warwick (2017), Yáňez (2018)
Human resources	Akdil, Ustundag, and Cevikcan (2018), Baena et al. (2016), Hecklau et al. (2016), Lichtblau et al. (2016), WMG–University of Warwick (2017), Yáňez (2018)
Product definition	Akdil, Ustundag, and Cevikcan (2018), Lichtblau et al. (2016), WMG–University of Warwick (2017), Yáňez (2018)
Managing operations: energy consumption management	Yáňez (2018)
Managing operations: quality management	Yáňez (2018)
Managing operations: supply chain management	Akdil, Ustundag, and Cevikcan (2018), Barreto, Amaral, and Pereira (2017), Hofmann and Rüsch (2017), Lichtblau et al. (2016), Luo et al. (2016), Szoda (2017), Tjhajono et al. (2017), WMG–University of Warwick (2017), Yáňez (2018)

3. Assessing the Extent of the Circular Economy Focus in Industry 4.0 Readiness

Industry 4.0 holds considerable promise for sustainable industrial value creation. While it is still regarded as a manufacturing paradigm that is still new, the emerging literature based on recent developments in the field suggests that it is possible to postulate likely positive impacts that Industry 4.0 can have from a circular economy perspective even without explicitly incorporating CE considerations into Industry 4.0 actions, projects, and programmes.

The term 'lean manufacturing' was formally coined by Womack and Jones (1996) to emphasise the importance of reducing what the Japanese automotive industry referred to as the 'seven deadly wastes'. A reduction of these wastes will have a beneficial impact from a CE perspective, even without a firm explicitly incorporating CE aspects into their strategic and operational planning (Wagner, Herrmann, and Thiede, 2017). The seven deadly wastes are: transport, inventory, motion, waiting, over-processing, overproduction, and defects. These are popularly referred to by the mnemonic TIMWOOD. Table 3.3 shows how Industry 4.0 can contribute towards a CE through the reduction of TIMWOOD, which in turn can lead to the reduction in the use of material and energy resources.

Table 3.3: Industry 4.0 and TIMWOOD Reduction for a Circular Economy

Seven deadly wastes	How Industry 4.0 can eliminate and/or minimize the seven deadly wastes
Transport (T)	• Processes located close to each other enable timely direct material movement • Streamlined production pathway reduces needless transport • Long and complex warehousing and material-handling systems avoided
Inventory (I)	• Enables working with smaller batch sizes due to reduced set-up times • Facilitates easier implementation of pull systems
Motion (M)	• Optimised workstation layouts lead to the smooth transfer of parts and materials leading to less worker effort • Redesigned layouts and workplaces and smaller batch sizes enable less movement of materials internally

Seven deadly wastes	How Industry 4.0 can eliminate and/or minimize the seven deadly wastes
Waiting (W)	• All operations run on schedule leading to less/no idling of subsequent workstations • Deliveries from suppliers and other departments arrive on time • Machines are well maintained with, therefore, less downtime • Well-trained workers and better-maintained machines lead to improved worker-machine coordination • Reduced or no waiting time since there is less/no rework of a product
Overproduction (O)	• Smaller batch size production possible through more reliable processes • Stable production schedules, balanced lines, and no bottlenecks become possible • Closer cooperation with customers leads to production based on actual demand
Over-processing (O)	• Standard operating procedures, well-trained workers, clear specifications, and explicit quality standards lead to optimal processing
Defects (D)	• Trained workers improved and standardised processes, closer coordination with suppliers, and reduced operator errors minimise defects and rework

Note: TIMWOOD refers to the seven deadly sins as listed in the table.
Source: Womack and Jones (1996).

At the heart of manufacturing in Industry 4.0 is the 'smart factory', where there is vertical integration of smart production systems, horizontal integration of value-chain systems, and 'end-to-end' or through-engineering across the entire value chain (Stock and Seliger, 2016; Mohr and Khan, 2015). The cyber-physical production system (CPPS) in a 'smart factory' uses sensor systems to identify and localise value creation entities, such as other machines, products being made, and people. Based on the monitored 'smart data', the actuators in the equipment respond in real-time to changes. The exchange of smart data between the value creation entities and the value chain is executed through the cloud. Table 3.4 shows how these value-creating factors can contribute towards a CE.

Table 3.4: Contribution by Value-creating Factors in Industry 4.0 Towards a Circular Economy

Value-creation factors	Contribution towards waste reduction and circular economy
Equipment	• Automated machine tools and robots work collaboratively with other value-creation factors. These smart machines are likely to be organised into modular working stations, which are error-proofed and have 'plug and produce' capability. • Existing manufacturing equipment can be retrofitted with sensors, actuators, and control logics as a cost-efficient way of upgrading to reduce the heterogeneity of equipment within the factory. • In addition to economic and environmental dimensions of sustainability, this could enable small and medium-sized enterprises to move towards Industry 4.0.

Value-creation factors	Contribution towards waste reduction and circular economy
People	• Overall decrease in the number of workers, but with a high percentage of knowledge workers who will increasingly have to monitor the CPPS, engage in decentralised decision-making, and participate in through-engineering activities. • As knowledge workers and, with responsibility for decentralised decision-making, these workers will have to be extensively trained to effectively use smart data and support tools based on AI. • Equipped with smart watches, 'smart operators' will receive, monitor, and take action in real-time to prevent failures and machine downtime.
Organisation	• Decentralised decision-making with local information being used by workers and machines in conjunction with AI helps the CPPS to find the optimum balance between the highest possible capacity utilisation at each work station and the continuous flow of goods. • If the organisation is suitably structured to foster decentralised decision-making and collaboration along the supply chain with a focus on resource conservation, then the implementation of smart grids, smart logistics, customer relationships, and other integrative approaches can promote holistic resource efficiency.
Process	• The use of exponential technologies, such as additive printing and internally cooled tools for metal-cutting, can lead to the design of resource-conserving and sustainable manufacturing processes.
Product	• Smart products' can be designed based on 'cradle-to-cradle' principles with mass customisation becoming possible. Through the adoption of exponential technologies, integrated after-sales functionality and access for improved performance can be built in, leading to a lower total cost of ownership. • Through the application of identification systems for the recovery of products for remanufacturing and the real-time tracking of the performance of products at the customer end, the total costs of production and ownership can be reduced while promoting the sustainable use of resources.

AI = artificial intelligence, CPPS = cyber-physical production systems.
Source: Adapted from Stock and Seliger (2016); Kolberg and Zühlke (2015); and Mohr and Khan (2015).

However, rather than regarding Industry 4.0 technologies as contributing to a CE through waste reduction, it has been recently proposed that it would be beneficial if a roadmap could be developed to explicitly incorporate CE principles into Industry 4.0 approaches (De Sousa Jabbour et al., 2018). In this context, De Sousa Jabbour et al. (2018) suggested that it would be useful to examine how the six business actions proposed by the Ellen MacArthur Foundation, and referred to as the ReSOLVE framework, can be used to implement the principles of CE in Industry 4.0 approaches. These six principles ReSOLVE) are briefly summarised below (De Sousa Jabbour et al., 2018).

- Regenerate: Emphasises shifting to the use of renewable energy and materials. Biological cycles become important from the perspective of enabling the circulation of energy and materials, and in converting organic waste into sources of energy and raw material for other chains.
- Share: Goods and assets are shared between individuals and in such a 'shared economy' setting, products are designed to last longer with maintenance enabling the re-use and extension of product life.
- Optimise: This technology-centred strategy requires organisations to use exponential technologies to reduce waste in production systems across supply chains. This aspect has been summarised above in Tables 3.3 and 3.4.
- Loop: This emphasises the use of biological and technical cycles to recapture the value of organic waste. For instance, anaerobic digestion can recapture the value of some organic wastes through a biological cycle. Technical cycles based on good reverse logistics can recover and restore the value of used products and packaging through repair, reuse, remanufacture, and recycling approaches.
- Virtualise: This emphasises service-focused strategies, which replace physical with virtual and dematerialised products.
- Exchange: This involves adopting a technological substitution approach through innovation where old and non-renewable goods are replaced by more advanced and renewable ones. The advantage of this is that replacement by cheaper and renewable substitutes can mitigate the supply risks of scarce materials, such as rare earth elements.

If these types of principles can be incorporated explicitly into the actioning of the eight determinants in the proposed Industry 4.0 Framework (Appendix 1), then firms would have a Circular Economy-focused Industry 4.0 setting that can enhance profitability through sustainability.

Appendix 2 shows the 'Framework for Assessing the Extent of the Circular Economy Focus in Industry 4.0 Readiness.' The eight determinants are the same as in the I4R framework to ensure compatibility between the two frameworks. Each of these determinants consists of several elements which, collectively, will determine the extent of the CE focus with respect to each determinant. The CE-based elements for each of these determinants were synthesised from De Jesus et al (2018), De Sousa Jabbour et al. (2018), Jovanović, Filipović, and Bakićet (2017), Lieder and Rashid (2016), Malinauskaite et al. (2017), and SITRA (2016). Furthermore, CE-relevant aspects from Lichtblau et al. (2015), Nguyen, Stuchtey, and Zils (2014), PricewaterhouseCoopers (2014), WMG–University of Warwick (2017), and Yáňez (2018) were included in developing the elements.

4. Assessing the 'I4R' and the 'CE Focus in I4R' in a Manufacturing Firm Using the Proposed Frameworks

The proposed frameworks may be used by an investigator to assess I4R and CE focus in a manufacturing firm. The frameworks may be also used as a self-assessment tool by firms. The procedures for carrying out these assessments are described in Appendix 3 and Appendix 4. These two procedures involve following the steps summarised below. The steps described below are those that could be adopted by an investigator.

Step 1: Obtaining background information on the firm

Having obtained approval to carry out the study in a large manufacturing firm (e.g. a firm in automobile manufacturing, machine tool manufacturing, textile and garment manufacturing, etc.), it will first be necessary to have a general discussion with management on the competitiveness status of the firm, future strategic plans, the challenges faced, and risk mitigation strategies that the firm has put into place to meet these challenges. This information will be useful in placing the findings in context.

Step 2: Assessing 'Industry 4.0 Readiness'

This step aims at rating the elements under each determinant using Appendix 1. This will involve meeting the appropriate managers in charge of these areas and asking them to choose the level at which the firm is with respect to the elements of each of the eight determinants. The managers must be asked to provide evidence to support their rating. This must be recorded by the investigator. To illustrate this, Appendix 3 shows an example of a hypothetical rating (shaded in blue) of the levels of the four elements of Determinant 2 (plant and equipment).

If possible, it will be useful to ask a few managers to independently choose the level with respect to each element so that the bias of an individual manager is not reflected in the rating. Ideally, there should be congruence.

If there are differences in the ratings, then the analyst should probe further to identify the reasons for the different ratings and then eventually arrive at a consensus.

Step 3: Assessing the 'CE Focus in Industry 4.0 Readiness'

This step aims at rating the elements under each determinant using Appendix 2. As in Step 2, this will involve meeting the appropriate managers in charge of these areas and asking them to choose the level of CE focus at which the firm is with respect to the elements of each of the eight determinants. The managers must be asked to provide some examples to support their rating. This must be recorded by the investigator. To illustrate this, Appendix 4 shows a hypothetical rating (shaded in green) of the levels of the four elements of Determinant 2 (plant and equipment).

Step 4: Presentation of the findings

The results of both assessments can be summarised using Table A3.2 in Appendix 3 and Table A4.2 in Appendix 4. Table A3.2 can be used to develop a summary of the case study firm's Industry 4.0 Readiness and Table A4.2 can be used to develop a summary of the case study firm's 'Circular Economy Focus in Industry 4.0 Readiness'. The maximum values attainable for each determinant are shown in both tables. The actual values obtained and the maximum values can be depicted using a radar diagram. It is suggested that separate radar diagrams be drawn for 'Industry 4.0 Readiness' and for the 'Circular Economy Focus in Industry 4.0 Readiness'.

Step 5: Interpretation of the findings of Table A3.2 (summary of I4R)

This will be the most difficult part. However, it is suggested that the findings be discussed with the management of the firm to obtain their views on the options available to the firm to accelerate their transition to Industry 4.0.

Since there are 33 elements in assessing I4R, the maximum score achievable will be 132 (i.e. 33 x 4). The status of I4R may be classified as follows.

0–33	Hesitators
34–66	Potentialists

67–99	Experienced
100–133	Experts or frontrunners

Step 6: Interpretation of the findings of Table A4.2 (summary of CE Focus in I4R)

This, too, will require discussion with the management of the firm to obtain their views on what they plan to do to explicitly bring in a CE focus into their Industry 4.0 programme. A firm that can effectively build in a CE focus is likely to achieve greater effectiveness in its Industry 4.0 programme.

Since there are 14 elements in assessing the extent of CE focus in I4R, the maximum score achievable will be 56 (i.e. 14 x 4). The status of CE focus in I4R may be classified as follows.

0–14	Business as usual
15–28	CE beginners
29–42	CE fast adopters
43–56	CE leaders

Step 7: Developing a CE-adjusted I4R index

A hypothetical example is used to illustrate how an overall score for a CE-focused I4R index may be calculated as follows.

Suppose Firm A achieves the following scores:

Industry 4.0 Readiness Score	= 102 (out of a maximum of 132)		
Extent of Circular Economy Focus in Industry 4.0 Readiness	= 38 (out of a maximum of 56)		
Industry 4.0 Readiness Index	= 102/156	=	0.77
Circular Economy Focus in Industry 4.0 Readiness Index	= 38/56	=	0.68
Circular Economy Focused Industry 4.0 Readiness Rating (CEF I4R Rating)	= 0.77 x 0.68	=	0.52

5. Using the Proposed Frameworks as a Self-assessment Tool to Transition to a Circular Economy-focused Industry 4.0 Setting

Based on the two assessment frameworks and the proposed analysis, Figure 3.2 provides a schematic representation of possible combinations that an analyst may come across with respect to a firm's I4R and the extent of the CE focus in its I4R. The proposed matrix in Figure 3.2 shows several possible combinations, some which are likely to not be valid. For instance, it is unlikely that an I4 hesitator will be a CE leader. Similarly, it is unlikely that a I4 frontrunner will adopt a business-as-usual approach with respect to CE. Some unfeasible combinations are shown in the CE-I4R matrix. Once an investigator completes the analysis or a firm carries out a self-assessment, this matrix can be used to position the firm in the CE-I4R matrix.

Figure 3.2: Circular Economy-focused Industry 4.0 Readiness Matrix

		Status of CE Focus in I4R			
		Business as Usual (0–14)	CE Beginners (15–28)	CE Fast Adopters (29–42)	CE Leaders (43–56)
Industry 4.0 Readiness Status	Expert/ Frontrunner (100-133)	Unlikely			I4 and CE Champion
	Experienced (67-99)	Unlikely			
	Potentialists (34–66)	Unlikely			
	Hesitators (0-33)	I4 and CE Novice	Unlikely	Unlikely	Unlikely

CE = circular economy, I4 = Industry 4.0, I4R = Industry 4.0 readiness.
Source: Author.

Once the CE-I4R assessment is carried out, the next stage will be complex, where the firm will have to develop a blueprint for action to be taken to move towards the top-right-hand corner of the matrix to become an 'I4 and CE champion'. Extensive cross-functional discussions within the firm will be needed, and external guidance may have to be sought to bring in new ideas and fresh thinking to supplement internal expertise.

A recent study carried out PwC Strategy & Germany (Geissbauer et al., 2018) points out that for a firm to become a 'digital champion' in the context of Industry 4.0, it is necessary to cleverly design and develop effective business ecosystems (customer solutions ecosystems, operations ecosystems, technology ecosystems, and people ecosystems) that are supported by a visionary digital culture reflecting the vision of the leadership, the company's way of working, and skill development of people. Geissbauer et al. (2018), also suggested a six-step approach that can be taken to facilitate the planning to become a digital champion. This six-step approach has been adapted to develop a procedure that can be used by a firm to plan its move upwards in the CE-I4R matrix.

Step 1: Use the two assessment frameworks to reach a consensus on immediate feasible actions that can be taken

- The discussion here should focus on the determinants that should receive priority and which of the elements within these determinants can be upgraded quickly to move forward so that customer value and competitiveness can be enhanced.
- If the two assessments have been carried out with care, then the results can provide transparency that can enable discussions to be held without bias or apportioning blame.

Step 2: Use the outcomes of the discussion in Step 1 to define a vision for the short term and the longer term

- Senior management can use the outcomes of the discussions in Step 1 to define a vision for the short and longer terms.
- The vision can be debated using customer value propositions and stakeholder aspirations as a basis for prioritising actions to be taken to achieve the vision.

- This step should logically conclude with agreement on the actions, projects, and programmes to be undertaken to achieve the vision.

Step 3: Identify the partnerships needed both at the upstream and downstream end of the supply chain to implement the actions, projects, and programmes

- Implementation of the projects and programmes will require the cooperation of suppliers (including lower-tier suppliers as well), distributors, retailers, and end consumers. The degree of cooperation needed with these entities will vary.
- This will require improving channels of communication along the supply chain and the identification of solutions that may have to be implemented along the supply chain.
- Arriving at the solutions will involve looking at interfaces, interdependencies, and information flows, etc. throughout the supply chain so that seamless integration can be achieved.
- These initiatives will then become an integral part of the actions, projects, and programmes that have been identified in Step 2.

Step 4: Appoint a steering committee to review the implementation of the actions, projects, and programmes and ensure that the CE-I4R transition proceeds as envisaged

- A steering committee comprising of senior managers who have the authority to make investment decisions should be appointed to review the progress and monitor key milestones.
- Discriminatory funding may have to be allocated to high-priority projects based on actual need.
- The steering committee may use ‘stage-gate’ models to review progress and take corrective actions.

Step 5: Build internal capabilities as well as supply chain capabilities to enable effective implementation

- Capabilities will need to be built in each determinant to move from a lower level to a higher one. These will be part of the projects and programmes identified.

- This will require working with internal as well as external human assets.
- Capability building may be implemented using agile project management techniques that utilise scrum and sprint approaches so that key skills and related resources can be shared amongst the projects quickly.

Step 6: Strive for perfection through radical improvements (kaikaku) supported by continuous improvement (kaizen)

- While the upgrading efforts would normally be expected to adopt a kaikaku (radical) approach, the projects, once implemented, will need continuous improvement (kaizen) so that the full value of the CE-I4R can be realised.
- Such kaizen efforts can also generate information needed for newer projects that may be needed to keep progressing.

In recent years the interest in assessing I4R at the firm level has intensified. Several studies have been carried out, mainly by leading consulting firms, to assess the I4R firm. However, these studies have not attempted to link I4R with CE. This chapter, while adopting an eclectic approach to develop an I4R assessment framework, has attempted to overcome this shortcoming by also developing a companion assessment framework that can assess the CE focus in I4R. Together these two frameworks can enable a firm to carry out a self-assessment of its I4R and its CE focus in I4R. Detailed procedures for carrying out the relevant analysis have been provided and managerial interventions needed for a firm to become a 'CE and Industry 4.0 champion' have been suggested.

The frameworks, after discussion and improvement, can be circulated by ERIA to help firms carry out CE-focused I4R self-assessments. It may also be useful to extend the two firm-level assessment frameworks to the level of a supply chain so that the focal firm in a supply chain can initiate action to help the smaller entities in the supply chain to upgrade their I4R with a CE focus.

References

Akdil, K.L., A. Ustundag, and E. Cevikcan (2018), 'Maturity and Readiness Model for Industry 4.0 Strategy,' in A. Ustundag and E. Cevikcan (eds.), *Industry 4.0: Managing the Digital Transformation*. Cham, Switzerland: Springer International Publishing AG.

Albert, M. (2015), 'Seven Things to Know About the Internet of Things and Industry 4.0', *MMS*, September Issue, pp.75–81.

Baena, F., A. Guarin, J. Mora, J. Sauza, and S. Retat (2016), 'Learning Factory: The Path to Industry 4.0', *Procedia Manufacturing*, 9, pp.73–80.

Barreto, L., A. Amaral, and T. Pereira (2017), 'Industry 4.0 Implications in Logistics: An Overview,' *Procedia Manufacturing*, 13, pp.1245–52.

D'Aveni, R. (2015), 'It's Happening, and It Will Transform Your Operations and Strategy', *Harvard Business Review*, May Issue, pp.41–48.

De Jesus A., P. Antunes, R. Santos, and S. Mendonca (2018), 'Eco-innovation in the Transition to a Circular Economy: An Analytical Literature Review', J*ournal of Cleaner Production*, 172, pp.2999–3018.

De Sousa Jabbour, A.B.L., C.J.C. Jabbour, M.C. Filho, and D. Rouband (2018), 'Industry 4.0 and the Circular Economy: A Proposed Research Agenda and Original Roadmap for Sustainable Operations', *Annals of Operations Research*, pp.273–86.

Deloitte (2015), *Industry 4.0: Challenges and Solutions for the Digital Transformation and Use of Exponential Technologies*. Zurich, Switzerland: Deloitte AG.

Geissbauer, R., E. Lübben, S. Schrauf, and S. Pillsbury (2018), *Global Digital Operations Study 2018 – Digital Champions – How Industry Leaders Build Integrated Operations Ecosystems to Deliver End-to-End Customer Solutions*. PwC Strategy & Germany.

Hermann, M., T. Pentek, and B. Otto (2015), 'Design Principles for Industrie 4.0 Scenarios: A Literature Review', *Working Paper No. 01/2015*, St. Gallen: Technische Universitat Dortmund.

Hecklau, F., M. Galeitzke, S. Flachs, and H. Kohl (2016), 'Holistic Approach for Human Resource Management in Industry 4.0', *Procedia CIRP*, 54, pp.1–6.

Hofmann, E. and M. Rüsch (2017), 'Industry Current Status as Well as Future Prospects on Logistics,' *Computers in Industry*, 89, pp.23–34.

Iansiti, M. and K.R. Lakhani (2014), 'Digital Ubiquity: How Connections, Sensors, and Data are Revolutionizing Business', *Harvard Business Review*, November Issue, pp.91–99.

International Telecommunication Union (ITU) (2015), *Measuring the Information Society Report*. Geneva: ITU.

Jovanović, B., J. Filipović, and V. Bakić (2017), 'Energy Management System Implementation in Serbian Manufacturing – Plan-Do-Check-Act Cycle Approach', *Journal of Cleaner Production*, 162, pp.1144–56.

Kolberg, D. and D. Zühlke (2015), 'Lean Automation Enabled by Industry 4.0 Technologies', *IFAC-PapersOnLine*, 48(3), pp.1870–75.

Li, S., L.D. Xu, and S. Zhao (2015), 'The Internet of Things: A Survey', *Information Systems Frontiers*, 17, pp.243–59.

Li, S., T. Tryfonas, and H. Li (2014), 'The Internet of Things: A Security Point of View', *Internet Research*, 26(2), pp.337–59.

Lichtblau, K., V. Stich, R. Bertenrath, M. Blum, M. Bleider, A Millack, K. Schmitt, E. Schmitz, and M. Schröter (2015), *IMPULS-Industrie 4.0 Readiness. Impuls-Stiftung des VDMA*, Aachen-Köln.

Lieder, M. and A. Rashid (2016), 'Towards Circular Economy Implementation: A Comprehensive Review in Context of Manufacturing Industry', *Journal of Cleaner Production*, 115, pp.36–51.

Luo, H., M. Zhu, S. Ye, H. Hou, Y. Chen and L. Bulysheva (2016), 'An Intelligent Tracking System Based on Internet of Things for the Cold Chain', *Internet Research*, 26(2), pp.435–45.

Malinauskaite, J., H. Jouhara, D. Czajczynska, P. Stanchev, E. Katsou, P. Rostkowski, R.J. Thorne, J. Colon, S. Ponsa, F. Al-Mansour, L. Anguilano, R. Krzyzynska, I.C. Lopez, A. Vlasopoulos, and N. Spencer (2017), 'Municipal Solid Waste Management and Waste-to-energy in the Context of a Circular Economy and Energy Recycling in Europe', *Energy*, 141, pp.2013–44.

Mohr, S. and O. Khan (2015), '3D Printing and Its Disruptive Impacts on Supply Chains of the Future', *Technology Innovation Management Review*, 5(11), pp.20–25.

Nguyen, H., M. Stuchtey, and M. Zils (2014), 'Remaking the Industrial Economy', *McKinsey Quarterly*, February 2014, pp.1–17.

PricewaterhouseCoopers (2014), *Industry 4.0 – Opportunities and Challenges of the Industrial Internet*. PricewaterhouseCoopers Aktiengesellschaft Wirtschaftsprüfungsgesellschaft.

RolandBerger (2014), 'Industry 4.0 the New Industrial Revolution: How Europe Will Succeed', *Think Act*, March 2014 Issue, Munich: RolandBerger Strategy Consultants GMBH.

Rüßmann, M., M. Lorenz, P. Gerbert, M. Waldner, J. Justus, P. Engel, and M. Harnisch (2015), 'Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries', 9 April, The Boston Consulting Group.

Schumacher, A., S. Erol, and W. Sihn (2016), 'A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises', *Procedia CIRP*, 52, pp.161–66.

Schwab, K. (2016), *The Fourth Industrial Revolution*. Geneva: World Economic Forum.

SITRA (2016), 'Leading the Cycle: Finnish Roadmap to a Circular Economy 2016-2025', *SITRA Studies*, 121, SITRA.

Stock, T. and G. Seliger (2016), 'Opportunities of Sustainable Manufacturing in Industry 4.0', *Procedia CIRP*, 40, pp.536–41.

Szoda, N. (2017), 'Industry 4.0 and Its Impact on the Functioning of Supply Chains', *Scientific Journal of Logistics*, 13(4), pp.401–14.

Tjahjono, B., C. Esplugues, E. Ares, and G. Pelaez (2017), 'What Does Industry 4.0 Mean to Supply Chain', *Procedia Manufacturing*, 13, pp.1175–82.

Ubisense (2015), *2014 Smart Manufacturing Technologies Survey*. Ubisense.

Wagner, T., C. Herrmann, and S. Thiede (2017), 'Industry 4.0 Impacts on Lean Production Systems', *Procedia CIRP*, 63, pp.125–31.

Weber, C., J. Königsberger, L. Kassner, and B. Mitschange (2017), 'M2DDM - A Maturity Model for Data-Driven Manufacturing', *Procedia CIRP*, 63, pp.173–78.

Whitmore, A., A. Agarwal, and L.D. Xu (2015), 'The Internet of Things – a Survey of Topics and Trends', *Information System Frontiers*, 17, pp.261–74.

WMG–University of Warwick (2017), An Industry 4 Readiness Assessment Tool. University of Warwick. https://warwick.ac.uk/fac/sci/wmg/research/scip/industry4report (accessed 9 April 2018).

Womack, J.P. and D.T. Jones (1996), 'Beyond Toyota: How to Root Out Waste and Pursue Perfection', *Harvard Business Review*, September–October Issue, pp.140–58.

Yáňez, F (2018), *The Goal Is Industry 4.0: Technologies and Trends of the Fourth Industrial Revolution*. San Bernardino, CA: independently published.

Appendix 1: A Framework for Assessing the Status of Industry 4.0 Readiness in Manufacturing

This framework has been developed based on a synthesis of recent literature. The details of all the references and how they were used to arrive at the criteria were presented at the ERIA Meeting in May 2018.

Determinant 1: Strategy and Organisation					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extent of Industry 4.0 emphasis in strategy formulation and implementation	Industry 4.0 has not been considered at all	Industry 4.0 is of interest at the departmental level but is not explicitly incorporated into corporate strategy	Industry 4.0 is recognised as important and is being introduced at an elementary level into the strategy formulation process	An Industry 4.0 strategy has been developed and implementation is in progress in stages	An enterprise-wide Industry 4.0 strategy has been implemented and is being continuously reviewed and updated
Interfirm collaboration	There is no cross-functional collaboration and the various departments adopt a 'functional silo' mentality	Some limited cooperation exists between the departments in areas such as sales and operations planning	Departments are willing to work together and share information, and the use of information technology (IT) has facilitated this	Departments realise the value of cross-functional collaboration to improve performance and use IT-based interventions, such as enterprise resource planning (ERP) systems	Cross-functional collaboration is the norm and the use of IT-based interventions has enabled the extensive sharing of information

Determinant 1: Strategy and Organisation					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Critical allocation of funds for Industry 4.0 investment	Has not been considered at all	Funds are allocated selectively, and incrementally, when requested by a department	Seed funding has been allocated at a basic level	Investments have been made in selected areas	Enterprise-wide investments have been made
Measuring the impact of Industry 4.0 implementation	No key performance indicators (KPIs) exist	No KPIs exist that assess the status of Industry 4.0 implementation and/or the enhanced performance arising out of Industry 4.0 introduction	A preliminary set of KPIs exist that assess the status of Industry 4.0 implementation and the enhanced performance arising out of Industry 4.0 introduction	A comprehensive set of KPIs is used to assess the status of Industry 4.0 implementation and the enhanced performance arising out of Industry 4.0 introduction	A comprehensive set of KPIs to assess Industry 4.0 implementation and impact has been formulated, is used enterprise-wide, and is integrated into the strategic planning process
Leadership	Top management has not recognised the value of Industry 4.0 and adopts a 'business-as-usual' attitude	The leadership is making preliminary investigations into the feasibility of adopting Industry 4.0 and the potential benefits to be gained	The leadership is convinced of the potential benefits to be gained through the adoption of Industry 4.0 and has commenced piloting and developing an implementation plan	The leadership shows total commitment by being involved in implementation and following up through reviews and providing additional resources as needed	There is enterprise-wide support for Industry 4.0; a culture of sharing lessons learned and disseminating the knowledge gained is prevalent
Innovation Orientation	Traditional method of using a 'funnel of ideas' and selecting projects	Adoption of a technology-push model along the lines of the linear model of innovation	Identification of customer needs triggers innovation and the adoption of a demand-pull approach	Adoption of 'open innovation' that incorporates knowledge from within the organisation and selected external entities	Supply chain-wide adoption of 'open innovation', incorporating knowledge from suppliers, customers, and other technology partners

Assessment Criteria	Determinant 2: Plant and Equipment				
	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Plant and equipment readiness for Industry 4.0	Not suitable for an Industry 4.0 model	Will need substantial overhaul for Industry 4.0 readiness	Some of the plant and equipment can be upgraded for Industry 4.0 without disruption	Most of the plant and equipment meet Industry 4.0 requirements and the rest can be upgraded	Plant and equipment meet Industry 4.0 requirements
Machine and system infrastructure	Machines and systems cannot be controlled through information technology (IT)	Some machines can be controlled through IT but there is no machine-to-machine (M2M) connectivity	Some machines can be controlled through IT and have M2M capability	All machinery can be controlled through IT and there is partial M2M	All machinery can be completely controlled through IT and have full M2M capability
Autonomously guided workpieces	No autonomously guided workpieces in use	Autonomously guided workpieces are not in use, but business cases for their adoption are being prepared for consideration	Autonomously guided workpieces are being piloted	Autonomously guided workpieces are used in selected areas	Autonomously guided workpieces are widely adopted with continuous improvements being made in their use
Maintenance of plant and equipment	Only breakdown maintenance	Breakdown maintenance kept to a minimum through preventive and periodic (time-based) maintenance	Predictive maintenance carried out along with retrofitting and/or modifying equipment to facilitate effective preventive maintenance	Maintenance prevention that focuses on the design of new equipment based on evidence-based studies of the weaknesses of existing machines	Total productive maintenance fully implemented and controlled by a cyber-physical system

Determinant 3: Information Technology Systems and Data Management					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Seamless system-integrated information sharing	No system-integrated information sharing	Some information sharing amongstst departments through the use of information technology (IT)	In-company information sharing through the use of IT and selective use of enterprise resource planning (ERP) systems	There is comprehensive in-company system-integrated information sharing along with some external system integration	Complete and seamless in-company system-integrated information sharing along with substantial external system integration
Cloud usage	Not in a position to consider it due to lack of infrastructure and skills	Cloud solutions not used even though opportunities exist for use	Plans have been developed and some partial testing has been carried out using cloud-based software, data storage, and analysis	Cloud-based solutions have been implemented successfully in some areas of the business	Cloud-based solutions have been implemented successfully across most or all areas of the business
IT and data security	Not a concern and nothing has been planned	IT security as an important issue is recognised and preliminary steps have been taken for protection	IT security solutions have been implemented in multiple areas of the business	IT security solutions have been comprehensively implemented across the business and are constantly monitored for bridging gaps that arise with time	IT security solutions, with continuous upgrading, have been implemented across the business and have been extended to cover data and information sharing with all relevant external partners
Operations data collection for internal process improvement	No formal data collection system; data is collected manually by departments for their own usage as needed	Required data is collected digitally by some departments and data available is current	Data is collected digitally by most departments	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

Determinant 3: Information Technology Systems and Data Management					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Operations data usage	Collected data is not integrated with the company's performance measurement system and is used mainly for reporting	Collected data is made available for integration with the company's performance measurement system and is used selectively for remedial action (e.g. quality improvement)	Data is integrated with the company's performance measurement system and used for performance improvement (e.g. to reduce downtime, reduce inventory, improve capacity utilisation etc.)	Comprehensive integration with the company's performance measurement system; used for performance improvement, performance optimisation, and improving supply chain performance	Effective integration with the company's performance measurement system, thereby enabling a dashboard perspective of all operations that enables performance improvement and optimisation across the supply chain
Virtualisation	There is awareness but no plans to develop the capacity	Use of some operational processes management software	Use of operational processes management software along with supervisory control and data acquisition (SCADA)	Comprehensive use of operational processes management software including manufacturing execution systems (MES), computerised maintenance management systems (CMMS), and SCADA	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)

Determinant 4: Human Resources					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
IT capabilities	Only basic IT skills scattered throughout the enterprise	Some information sharing amongst departments through the use of information technology (IT)	In-company information sharing through the use of IT and selective use of enterprise resource planning (ERP) systems	There is comprehensive in-company system-integrated information sharing along with some external system integration	Complete and seamless in-company system-integrated information sharing along with substantial external system integration
Industry 4.0 digital training	Basic or no knowledge of Industry 4.0 technologies amongst management and operations staff	Management and operations staff have been provided basic training on Industry 4.0, its benefits, and the new ways of working needed	New skills needed have been identified in relation to Industry 4.0 strategy; relevant staff have been provided training and new staff with required skills have been recruited	Advanced IT skills needed for Industry 4.0 IT systems and data usage (in areas such as ERP, MES, SCADA, product life management (PLM), CIMM, and digital twins), and business analytics (descriptive, diagnostic, predictive, and prescriptive) are now available within the enterprise	Cloud-based solutions have been implemented successfully across most or all areas of the business
Human-machine interface	Only direct human – machine interaction	Staff use remote control devices for routine machine interaction	Routine machine interaction no longer needed; capabilities are built into the machines	Ubiquitous access to all machines and devices through user-friendly interfaces	Independent monitoring built into the cyber-physical production systems
Skills for people-system Collaboration	Traditional system of collaboration and communication between people and systems through meetings and the exchange of hard copy information	Horizontal integration of information systems along the horizontal value chain (sales, outbound logistics, manufacturing, inbound logistics, and procurement)	Data is collected digitally by most departments	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

Determinant 5: Product Definition					
Assessment Criteria	Readness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Product customisation	Product is a standard offering; no customisation possible	Products are made in large batches; some limited, late customisation possible in some products (e.g. changing the colour)	Products have standardised bases, but limited features can be customised in many products (assemble to order (ATO))	Mass customisation (ATO) possible in all products, but possibilities are constrained by inability of suppliers to quickly deliver the components needed for customisation	Late differentiation available for all make-to-order (MTO) products (batch size is 1)
Digital features of the product	Product is common and has many substitutes	Product is competitive but shows only physical value	Product value arises only due to the protected intellectual property used	Product value arises from the protected intellectual property used and some digital features	Product value arises from the protected intellectual property used and extensive digital features
Management of the product life cycle	Traditional approach based on a supply-push approach with limited or no inputs from other functional areas within the firm and downstream entities in the supply chain	A product data management (PDM) system is used	Engineering product lifecycle management (PLM) solution is used in design, manufacturing, and after-sales)	PLM solution is fully implemented within the enterprise and along the supply chain, both downstream and upstream	A digital twin is used for the development of the product and the designing of the production processes needed, to produce the designed product, so that simulation and testing can be carried out prior to carrying out actual operations

Determinant 6: Managing Operations – Energy Consumption Management					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Monitoring energy consumption	Consumption information provided by the energy provider	Products are made in large batches; some limited, late customisation possible in some products (e.g. changing the colour)	Products have standardised bases, but limited features can be customised in many products (assemble to order (ATO))	Mass customisation (ATO) possible in all products, but possibilities are constrained by inability of suppliers to quickly deliver the components needed for customisation	Late differentiation available for all make-to-order (MTO) products (batch size is 1)
Managing energy consumption	Conventional power management	Regular energy audits carried out for developing improvement initiatives	Advanced energy saving systems have been installed	Energy consumption aspects are built into product and process design to proactively reduce energy usage	Product value arises from the protected intellectual property used and extensive digital features
Energy systems	Energy consumption on demand	Control of energy demand	Power self-generation	Energy storage systems have been installed and the energy demand curve is well balanced	The enterprise has minimal demand on the external energy provider and, through its own self-generation, has a positive net balance

Determinant 7: Managing Operations – Quality Management					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Quality assurance	Heavy reliance on inspection at incoming and finished stages	Products are made in large batches; some limited, late customisation possible in some products (e.g. changing the colour)	Products have standardised bases, but limited features can be customised in many products (assemble to order (ATO))	Mass customisation (ATO) possible in all products, but possibilities are constrained by inability of suppliers to quickly deliver the components needed for customisation	Late differentiation available for all make-to-order (MTO) products (batch size is 1)
Quality traceability in the supply chain	Quality issues are handled by accepting rejects and providing replacements. Causes of problems cannot be traced	Quality issues are traceable down to the batch based on product parameters	Quality issues are traceable down to the batch based on both product and production process parameters	Use of advanced control systems (e.g. artificial vision) along with machine learning systems and automatic adjustment of machine parameters to achieve zero defects.	Product value arises from the protected intellectual property used and extensive digital features

Determinant 8: Managing Operations – Supply Chain Management					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Customer demand management and supply chain integration	Based on historical demand patterns and forecasts	Products are made in large batches; some limited, late customisation possible in some products (e.g. changing the colour)	Products have standardised bases, but limited features can be customised in many products (assemble to order (ATO))	Mass customisation (ATO) possible in all products, but possibilities are constrained by inability of suppliers to quickly deliver the components needed for customisation	Late differentiation available for all make-to-order (MTO) products (batch size is 1)
Supply chain visibility and integration	Each entity in the supply chain deals with the other at arm's length	Requirements and delivery information shared selectively with critical suppliers and customers, respectively	Site location, capacity, inventory, and operations are visible between selected critical suppliers and customers	Site location, capacity, inventory, and operations are visible to all Tier 1 suppliers and customers	Site location, capacity, inventory and operations are visible throughout the supply chain and is used in real-time for monitoring and optimisation
Inventory management	Manual systems used to update inventory levels at periodic intervals	Computerised database for recording inventory levels and is updated manually at periodic intervals	ERP system is used to update inventory levels	The inventory database is updated through the use of smart devices at the point of use	The inventory database is updated in real-time through the use of smart devices at the point of use

Determinant 8: Managing Operations – Supply Chain Management					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Warehouse management	Manual warehousing practices – receiving, storage, picking, and staging	Partial automation of receiving, storage, picking, and staging	Automated storage and retrieval systems	Automated warehouse integrated within the supply chain	Only few automated warehouses in the supply chain due to complete synchronisation with only consolidation points
Transportation	Own or customer vehicles used to deliver to customers	Use of second-party logistics (2PL) service providers for defined deliveries	Use of third-party logistics (3PL) service providers to manage transportation within the supply chain	Use of fourth-party (4PL) service providers to integrate logistics within the supply chain and reduce lead times	Use of 4PL service providers and autonomous transportation

Appendix 2: Assessing the Extent of the Circular Economy Focus in Industry 4.0 Readiness

Determinant 1: Strategy and Organisation					
Circular Economy (CE) Focus Criteria	Focus Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extent to which the business model of the firm allows for the leasing or renting out of the outputs so that it can be ensured that materials are returned for reuse	Top management has no interest in a CE focus	Top management has expressed interest and preliminary ideas are being exchanged	The organisation has worked out a strategy to adopt the CE business model in stages	The new business model is being implemented for some market segments and is being updated based on experience gained	The new business model is completely implemented across all market segments
Extent to which the firm requires its suppliers and subcontractors to provide parts and components that can be easily repaired, instead of fixed and single-use parts	Relationships with suppliers and subcontractors are at arms-length and is based only on price	Supplier and subcontractor relationships are good but there is no focus on easy repair and reuse aspects with respect to supplies.	The firm designs parts and components with a focus on easy repair and reuse and passes on the specifications to suppliers and subcontractors	There is early supplier involvement (ESI) from the concept development, design, and specification development stages to produce parts and components with a focus on easy repair and reuse	Comprehensive ESI from concept development, design, and specification stages, and to create an ecosystem that will support circular product designs

Determinant 1: Strategy and Organisation					
Circular Economy (CE) Focus Criteria	Focus Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extent to which the firm has developed profit-sharing models and incentives to encourage partners to work with the firm to adopt CE principles and ensure that the principle of 'multiple cycles of disassembly and reuse' is adhered to	None have been developed and top management does not subscribe to the need for such a model	There is interest but work on the development of such models is still at a preliminary stage	Models have been developed and pilot tested with some critical partners but are not ready for full implementation	Models have been developed and implemented successfully with some critical partners based on trust, information exchange, and shared understanding of the value of adapting CE practices	Comprehensive models have been developed and implemented successfully with all partners based on trust, information exchange, and shared understanding of the value of adapting CE practices
Extent of emphasis of eco-innovation principles in innovation that includes increased functionality, modular parts, enabling reuse of parts, refurbishment, use of non-toxic and pure components (to enable return to the biosphere) and de-materialisation (e.g. use of the internet and reduced packaging)	No consideration of eco-innovation principles; the focus is mainly on cost reduction and improved performance, even if this means sacrificing eco-innovation principles	Incorporation of eco-innovation aspects are incidental (e.g. use of modular parts or reduced packaging) and are due to reasons of cost reduction	Eco-innovations aspects are incorporated explicitly only to meet regulatory requirements	There is conviction that eco-innovation is a priority and that it can make positive contributions to profitability	All innovation is explicitly required to incorporate eco-innovation principles and demonstrate positive contributions towards a CE

Determinant 2: Plant and Equipment					
Circular Economy (CE) Focus Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Capability of plant and equipment and facilities layout to adopt the principle of 'remanufacturing', consisting of disassembly, cleaning, inspection and sorting, reconditioning, and reassembly	Adoption of the remanufacturing principle will not be possible with the current facilities layout and production processes	Some sections of the production process can be converted to adopt remanufacturing, but the organisation has not initiated the move	The sections of the production process that can be converted to adopt remanufacturing are being suitably redesigned and renovated	Remanufacturing is adopted in several sections of the production process	The entire manufacturing facility is capable of adopting remanufacturing
Capability of plant and equipment and facilities layout to adopt resource conservative manufacturing (ResCoM, viz; conservation of energy, water, material, and value added through waste prevention and environmental protection)	Minimal or no capability to adopt ResCoM	Some sections of the production process can be converted to adopt ResCoM, but the organisation has not initiated the move	The sections of the production process that can be converted to adopt ResCoM are being suitably redesigned and renovated	ResCoM can adopted in several sections of the production process	The entire manufacturing facility is capable of adopting ResCoM

Determinant 3: Information Technology Systems and Data Management					
Circular Economy (CE) Focus Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extent of design of the information technology system and data management to quickly generate information needed for incorporating CE principles explicitly into the firm's operations (e.g. reverse logistics information needed for collection, sorting, remanufacturing, and refurbishment; tracking the location and condition of used devices and components, as well as storing bill-of-materials information; energy consumption and usage, etc.)	No consideration has been given to the generation of such information	The data needed may be available in a raw form, but the IT system software will have to be redesigned and upgraded to generate the information needed for incorporating CE principles	Some information is available and easily accessible for incorporating CE principles	Information within the firm can be easily accessed to assist in incorporating CE principles but only partial information is available from partners in the supply chain	Comprehensive information can be easily accessed both internally and from partners in the supply chain to assist in incorporating CE principles

Determinant 4: Human Resources					
Circular Economy (CE) Focus Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extent to which CE value networks have been built amongst stakeholders	No explicit efforts have been made	Employees of the firm are aware of the CE imperative and have adopted new ways of working to support the firm's initiatives in adopting CE-based approaches	Employees of the firm and critical suppliers, distributors, and retailers are aware of the CE imperative and have adopted new ways of working to support the firm's initiatives in adopting CE-based approaches	Employees of the firm, and all suppliers, distributors, and retailers are aware of the CE imperative and have adopted new ways of working to adopt CE-based approaches through the entire supply chain; initiatives are underway to convince and inform customers about maintenance and repair services, environmental impacts, materials that have been put in place to foster a circular economy	Employees of the firm, and all suppliers, distributors, and retailers are aware of the CE imperative and have adopted new ways of working to adopt CE-based approaches through the entire supply chain; consumers reinforce the CE-based approaches by demanding sustainable products, commodities, and services

Determinant 5: Product Definition					
Circular Economy (CE) Focus Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extent of 'regenerative design' considerations with distinction being made between 'technical nutrients' (materials that can be refurbished, reused, or recycled) and 'biological nutrients' (materials that can safely enter the biosphere)	No explicit consideration; design is based on cost and what is available; any regenerative design aspects that appear are incidental	Regenerative design aspects are focused mainly on technical nutrients. Biological nutrient focus is restricted to those needed because of regulatory requirements	Regenerative design is restricted to only what is designed by the firm; there is no requirement on suppliers to incorporate these design requirements into the parts and components that they supply	Some products are designed with comprehensive regenerative design considerations with the participation of some critical suppliers who incorporate these considerations into the parts and components that they supply	All products are designed with comprehensive regenerative design considerations with the complete participation of all suppliers who incorporate these considerations into the parts and components that they supply
Extent of 'critical material design' considerations, such as less material usage, miniaturisation, modularisation, less production processing, long-lasting products, ease of component reuse, and ease of remanufacturing	No explicit consideration; design is based on cost and what is available; any critical material design aspects that appear are incidental	Critical material design aspects are focused on just a few considerations and aspects mainly on technical nutrients; biological nutrients focus is restricted to those needed because of regulatory requirements	Critical material design is restricted to only what is designed by the firm; there is no requirement on suppliers to incorporate these design requirements into the parts and components that they supply	Some products are designed with comprehensive critical material design considerations with the participation of some critical suppliers who incorporate these considerations into the parts and components that they supply	All products are designed with comprehensive critical material design considerations with the complete participation of all suppliers who incorporate these considerations into the parts and components that they supply

Determinant 6: Managing Operations – Energy Consumption Management					
Circular Economy (CE) Focus Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extent to which 'waste-to-energy' (WtE) approaches, such as thermochemical conversion (combustion, gasification, pyrolysis, and refuse-derived fuel), physicochemical conversion (transesterification), and biochemical conversion (fermentation and anaerobic digestion) are used as a secondary resource to reduce the carbon footprint	None used	Thermochemical conversion approaches such as combustion (hot gases) and refuse-derived fuel (RFD) are used in an ad-hoc way	Thermochemical conversion approaches, such as combustion (hot gases) and refuse derived fuel (RFD), are used on a consistent and regular basis, and plans are underway to examine the feasibility of adopting other WtE approaches	Comprehensively used based on a sophisticated understanding of the nature of wastes generated by the firm	Comprehensively used across the supply chain based on a sophisticated understanding of the nature of wastes generated by the supply chain

Determinant 7: Managing Operations – Quality Management					
Circular Economy (CE) Focus Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extent to which a 'zero-defect' (ZD) approach is being used to eliminate waste	Defects are regarded as inevitable, and the emphasis is on reducing the extent	There is interest in moving towards a ZD target, and plans are being made	Formal ZD programmes have been initiated within the firm and some are being piloted	Formal ZD programmes have been initiated comprehensively within the firm with continuous monitoring and improvement	Formal ZD programmes have been initiated comprehensively within the firm and with all key partners in the supply chain

Determinant 8: Managing Operations – Supply Chain Management					
Circular Economy (CE) Focus Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Level of sophistication of the reverse logistics system from a CE perspective	No formal reverse-logistics capability; any collection from the downstream end of the supply chain is done on a needs basis	The firm is planning/ developing arrangements with its downstream supply chain partners to develop a collection, sorting, refurbishment, and remanufacturing mechanism to bring materials and used products only up to the firm	The firm, in collaboration with its downstream supply chain partners, has put in place a collection, sorting, refurbishment, and remanufacturing mechanism to bring materials and used products only up to the firm	The firm, in collaboration with some of its critical supply chain partners (both upstream and downstream), has put in place a collection, sorting, refurbishment, and remanufacturing, mechanism to bring materials and used products upstream to the relevant entities in the supply chain	The firm, in collaboration with all its supply chain partners (both upstream and downstream), has put in place a collection, sorting, refurbishment, and remanufacturing mechanism to bring materials and used products upstream to the relevant nodes in the supply chain
Extent of reverse-network-management capabilities	The firm has no capabilities to track the location and condition of used devices and components or gather bills-of-material (BOM) information	The firm is in the process of developing basic capabilities to track the location and condition of used devices and components, and gather BOM information	Through the use of advanced IT-based interventions, the firm can track the location and condition of some used devices and components, as well as BOM information, which are relevant only for its own use	Through advanced IT-based interventions, the firm and its critical supply chain partners can track the location and condition of used devices and components, as well as BOM information for their use	Through the use of advanced IT-based interventions, the firm and its supply chain partners can track the location and condition of used devices and components and also BOM information

Appendix 3: Procedure for Assessing the Industry 4.0 Readiness of a Manufacturing Firm

The eight determinants for assessing Industry 4.0 readiness (I4R) are as follows:

1. Strategy and organisation
2. Plant and equipment
3. Information technology systems and data management
4. Human resources
5. Product definition
6. Managing operations – energy consumption management
7. Managing operations – quality management
8. Managing operations – supply chain management

Each of these determinants consist of several elements which, collectively, will determine the Industry 4.0 readiness level with respect to each determinant. These elements are shown in Appendix 1, titled 'A Framework for Assessing the Status of Industry 4.0 Readiness in Manufacturing'.

The framework may be used to carry out an assessment of the I4R of any firm in the manufacturing sector. However, it is suggested that a study be carried out in a firm that is currently considered to be relatively advanced in manufacturing.

The following steps may be adopted in carrying out the case study.

Step 1: Obtaining background information of the case study firm

Having obtained approval to carry out the study in a large manufacturing firm (e.g. a firm in automobile manufacturing), it will first be necessary to have a general discussion with management on the competitiveness status of the firm, their plans for the future, the challenges faced, and risk mitigation strategies that the firm has put in place to meet these challenges. This information will be useful in placing the findings in context.

Step 2: Rating the 'Industry 4.0 readiness' of the elements of the eight determinants

This step aims at rating the elements under each determinant using Appendix 1. This will involve meeting the appropriate managers responsible for these determinants and asking them to choose the level at which the firm is with respect to the elements of each of the eight determinants.

If possible, it will be useful to ask a few managers to independently choose the level with respect to each element so that the bias of an individual manager is not reflected in the rating. Ideally, there should be congruence. If there are differences in the ratings, then the analyst should probe further to identify the reasons for the different ratings and then eventually arrive at a consensus.

The managers must be asked to provide evidence to support their rating. This must be recorded by the investigator. A hypothetical rating (shaded in blue) of the levels of the four elements of Determinant 2 is shown below in Table A3.1.

Table A3.1: A Hypothetical I4R Rating of Determinant 2 – Plant and Equipment

Determinant 2: Plant and Equipment					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Plant and equipment readiness for Industry 4.0	Not suitable for an Industry 4.0 model	Will need substantial overhaul for Industry 4.0 readiness	Some of the plant and equipment can be upgraded without disruption	Most of the plant and equipment meet Industry 4.0 requirements and the rest can be upgraded	Plant and equipment meet Industry 4.0 requirements

Determinant 2: Plant and Equipment					
Assessment Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Machine and system infrastructure	Machines and systems cannot be controlled through information technology (IT)	Some machines can be controlled through IT but there is no machine-to-machine (M2M) connectivity	Some machines can be controlled through IT and have M2M capability	All machinery can be controlled through IT and there is partial M2M	All machinery can be completely controlled through IT and have full M2M capability
Autonomously guided workpieces	No autonomously guided workpieces in use	Autonomously guided workpieces are not in use, but business cases are being prepared for consideration	Autonomously guided workpieces are being piloted	Autonomously guided workpieces are used in selected areas	Autonomously guided workpieces are widely adopted with continuous improvements being made in their use
Maintenance of plant and equipment	Only breakdown maintenance	Breakdown maintenance kept to a minimum through preventive and periodic (time-based) maintenance	Predictive maintenance carried out along with retrofitting and/or modifying equipment to facilitate effective preventive maintenance	Maintenance prevention that focuses on the design of new equipment based on evidence-based studies of the weaknesses of existing machines	Total productive maintenance fully implemented and controlled by a cyber-physical system

The following scores may be assigned for the different levels.

Level 0:	0	Level 1:	1
Level 2:	2	Level 3:	3
Level 4:	4		

For the illustrative example above, the scores for each of the elements would be as follows.

Plant and equipment readiness for Industry 4.0	2
Machine and system infrastructure	2
Autonomously guided workpieces	0
Maintenance of plant and equipment	1

The score for this determinant is therefore 5 out of a maximum possible score of 12.

The values may then be entered for the elements of this determinant in Table A3.2, the Industry 4.0 Readiness Assessment Summary.

Step 3: Interpretation of the findings of Table A2.2

This will be the most difficult part. However, it is suggested that the findings be discussed with the management of the firm to obtain their views on what the available options are to accelerate their transition to Industry 4.0.

Since there are 33 elements, the maximum score achievable will be 132 (i.e. 33 x 4). The status of I4R may be classified as follows.

0–33	Hesitators
34–66	Potentialists
67–99	Experienced
100–133	Experts or frontrunners

Table A3.2: Industry 4.0 Readiness Assessment Summary

Determinants of Industry 4.0 Readiness	Assigned Score	Maximum Score Attainable
Determinant 1: Strategy and Organisation		
Extent of Industry 4.0 emphasis in strategy formulation and implementation		4
Inter-firm collaboration		4
Critical allocation of funds for Industry 4.0 investment		4
Measuring the impact of Industry 4.0 implementation		4
Leadership		4
Innovation orientation		4
Sub total		**24**
Determinant 2: Plant and Equipment		
Plant and equipment readiness for Industry 4.0		4
Machine and system infrastructure		4
Autonomously guided workpieces		4
Maintenance of plant and equipment		4
Sub total		**16**
Determinant 3: Information Technology Systems and Data Management		
Seamless system-integrated information sharing		4
Cloud usage		4
Information technology (IT) and data security		4
Operations data collection for internal process improvement		4
Operations data usage		4
Virtualisation		4
Sub total		**24**
Determinant 4: Human Resources		
IT capabilities		4
Industry 4.0 digital training		4
Human-machine interface		4
Skills for people–system collaboration		4
Sub total		**16**

Determinants of Industry 4.0 Readiness	Assigned Score	Maximum Score Attainable
Determinant 5: Product Definition		
Product customisation		4
Digital features of the product		4
Management of the product life cycle		4
Sub total		**12**
Determinant 6: Managing Operations – Energy Consumption Management		
Monitoring energy consumption		4
Managing energy consumption		4
Energy systems		4
Sub total		**12**
Determinant 7: Managing Operations – Quality Management		
Quality assurance		4
Quality traceability in the supply chain		4
Sub total		**8**
Determinant 8: Supply Chain Management		
Customer demand management and supply chain integration		4
Supply chain visibility and integration		4
Inventory management		4
Warehouse management		4
Transportation		4
Sub total		**20**

Appendix 4: Procedure for Assessing the Industry 4.0 Readiness of a Manufacturing Firm

The eight determinants for assessing Industry 4.0 readiness (I4R) are as follows:

1. Strategy and organisation
2. Plant and equipment
3. Information technology systems and data management
4. Human resources
5. Product definition
6. Managing operations – energy consumption management
7. Managing operations – quality management
8. Managing operations – supply chain management

Each of these determinants consists of several elements, which, collectively, will determine the I4R level with respect to each determinant. These elements are shown in Appendix 1, titled 'A Framework for Assessing the Status of Industry 4.0 Readiness in Manufacturing'.

Appendix 3 shows how the extent of the circular economy (CE) focus can be assessed for each of these determinants. This assessment should be carried out at the same firm where the I4R assessment was carried out to enable assessment of the CE focus in that firm's I4R. The following steps may be used to carry out the CE focus assessment.

Step 1: Assessing the 'CE Focus in Industry 4.0 Readiness'

This step aims at rating the elements under each determinant using Appendix 3. As in the case of the I4R assessment, this too will involve meeting the appropriate managers in charge of these areas and asking them to choose the level of CE focus at which the firm is with respect to the elements of each of the eight determinants. The managers must be asked to provide some examples to support their rating. This must be recorded by the investigator. A hypothetical rating (shaded in green) of the levels of the four elements of Determinant 2 is shown in Table A4.1 below.

The following scores may be assigned for the different levels.

Level 0:	0
Level 1:	1
Level 2:	2
Level 3:	3
Level 4:	4

Table A4.1: A Hypothetical Circular Economy Focus Rating of Determinant 2 – Plant and Equipment

Determinant 2: Plant and Equipment					
Circular Economy (CE) Focus Criteria	Readiness Level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Capability of plant and equipment and facilities layout to adopt the principle of 'remanufacturing', consisting of disassembly, cleaning, inspection and sorting, reconditioning, and reassembly	Adoption of the remanufacturing principle will not be possible with the current facilities layout and production processes	Some sections of the production process can be converted to adopt remanufacturing, but the organisation has not initiated the move	The sections of the production process that can be converted to adopt remanufacturing are being suitably redesigned and renovated	Remanufacturing is adopted in several sections of the production process	The entire manufacturing facility is capable of adopting remanufacturing
Capability of plant and equipment and facilities layout to adopt resource--conservative manufacturing (ResCoM, viz; conservation of energy, water, material, and value added through waste prevention and environmental protection	Minimal or no capability to adopt ResCoM	Some sections of the production process can be converted to adopt ResCoM, but the organisation has not initiated the move	The sections of the production process that can be converted to adopt ResCoM are being suitably redesigned and renovated	ResCoM can be adopted in several sections of the production process	The entire manufacturing facility is capable of adopting ResCoM

For the illustrative example above, the scores for each of the elements would be as follows.

Capability of plant and equipment and facilities layout to adopt the principle of 'remanufacturing'	2
Capability of plant and equipment and facilities layout to adopt resource-conservative manufacturing (ResCoM)	2

The score for this determinant is therefore 4 out of a maximum possible score of 8. The values may then be entered for the elements of this determinant in Table A4.2, Circular Economy Focus in Industry 4.0 Readiness Summary.

Table A4.2: Circular Economy Focus in Industry 4.0 Readiness Summary

Determinants of Industry 4.0 Readiness	Assigned Score	Maximum Score Attainable
Area 1: Strategy and Organisation		
Extent to which the business model of the firm allows for the leasing or renting out of the outputs so that it can be ensured that materials are returned for reuse		4
Extent to which the firm requires its suppliers and subcontractors to provide parts and components that can be easily repaired, instead of fixed and single-use parts		4
Extent to which the firm has developed profit sharing models and incentives to encourage partners to work with the firm to adopt circular economy (CE) principles		4
Extent of emphasis of eco-innovation principles in innovation		4
Sub total		**16**
Area 2: Plant and Equipment		
Capability of plant and equipment and facilities layout to adopt the principle of 'remanufacturing'		4
Capability of plant and equipment and facilities layout to adopt resource conservative-manufacturing (ResCoM)		4
Sub total		**8**

Determinants of Industry 4.0 Readiness	Assigned Score	Maximum Score Attainable
Area 3: Information Technology Systems and Data Management		
Extent of design of the information technology system and data management to quickly generate information needed for incorporating CE principles explicitly into the firm's operations		4
Sub total		**4**
Area 4: Human Resources		
Extent to which CE value networks have been built amongst stakeholders		4
Sub total		**4**
Area 5: Product Definition		
Extent of 'regenerative design' considerations, with distinction being made between 'technical nutrients' and 'biological nutrients'		4
Extent of 'critical material design' considerations		4
Sub total		**8**
Area 6: Managing Operations – Energy Consumption Management		
Extent to which 'waste-to-energy' (WtE) approaches, such as thermochemical conversion, physicochemical conversion, and biochemical conversion, are used as a secondary resource to reduce the carbon footprint		4
Sub total		**4**
Area 7: Managing Operations – Quality Management		
Extent to which a 'zero-defect (ZD)' approach is being used to eliminate waste		4
Sub total		**4**
Area 8: Supply Chain Management		
Level of sophistication of the reverse logistics system from a CE perspective		4
Extent of reverse-network-management capabilities		4
Sub total		**8**