The design and validation of the Smart Industry Sustainability Scan: assessing the maturity of Industry 4.0 for sustainable manufacturing.

Author: Charlotte van Veen
University of Twente
P.O. Box 217, 7500AE Enschede
The Netherlands

ABSTRACT,
The fourth industrial revolution is currently changing the way manufacturers operate. Smart technologies enable to optimize production processes and resource efficiency. In this way smart factories are created, where all objects and processes are interconnected, responsive and flexible. In this paper, a maturity model for the assessment of the integration of Industry 4.0 and sustainability is developed. Existing maturity models do not focus on the sustainability part of Industry 4.0. Because while Industry 4.0 initially strives to achieve economic aims, it creates many opportunities for the achievement of ecological and social aims as well. Insight into the maturity of the integration of Industry 4.0 and sustainability is crucial for any manufacturing organization to compete in rapidly changing industrial dynamics. First an extensive literature review is done about the opportunities of sustainability in Industry 4.0, as well as the design of a maturity model. From this the model has been designed. It is then validated by gathering and analyzing the feedback of experts. With the use of the feedback, the model is improved, and the final model is presented. The Smart Industry Sustainability Scan consists of 33 questions, divided over the aspects Regulations & Policies, Strategy & Performance, Pollution, Resource circularity, Sustainable energy, and Social Sustainability. This research contributes to theory by providing a maturity model for the integration of Industry 4.0 and sustainability. The maturity model can be used in practice for manufacturers to assess their current performance on Industry 4.0 to enhance sustainable manufacturing. From there, practical suggestions can be made for the manufacturer to mature further on the aspects. Last, recommendations are made, limitations are identified, and the research is concluded.

Graduation Committee members:
Dr. R.P.A. Loohuis
Drs. P. Bliek

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1. INTRODUCTION

1.1 Background and relevance

Industry means the part of an economy that manufactures products in a highly automated and mechanized way (Lasi et al., 2014). Since the start of industrialization, radical technologies have caused paradigm shifts. These were afterwards named Industry 1.0 (the rise of water and steam powered mechanization), Industry 2.0 (the rise of electricity) and Industry 3.0 (the rise of digitalization). At this moment, we are experiencing the Fourth Industrial Revolution, also known as Industry 4.0, or Smart Industry. The term Industry 4.0 was first used in 2011 by Germany as part of a high-tech strategy, thereby introducing the idea of the fully integrated factory (Hofmann & Rüsch, 2017). It is unique that this industrial revolution is recognized as one while it is happening, which brings opportunities for organizations to co-shape their future (Hermann et al., 2016). Since the introduction of Industry 4.0 in 2011, attention for it has been growing. The initial aim of Industry 4.0 is one of economic nature, namely increasing productivity, revenue growth and competitive advantage. But in a world where sustainably increasingly becomes a theme, Industry 4.0 holds great opportunities for the development towards sustainable manufacturing as well (Bonilla et al., 2018).

To indicate the current performance on the integration of Industry 4.0 and sustainability in an organization, a maturity model can be used to assess the status quo. So far, available maturity models on Industry 4.0 focus on relevant dimensions to indicate the maturity level. However, sustainability has not played a significant role in them. In literature there has been focus on the link between Industry 4.0 and sustainability, or more specifically how smart technologies enable sustainable manufacturing. The purpose of this thesis is to develop a valid maturity model which assesses the integration of Industry 4.0 and sustainability of manufacturers. This is done through an extensive literature review. Next, the proposed model is validated by the gathering feedback from experts in the field of Industry 4.0 and sustainability. This feedback is then analyzed and implemented into the model to improve the proposed scan. This research contributes to the Business Administration domain by closing a gap between Industry 4.0 and sustainable manufacturing. Besides it is of practical use for organizations that aim to mature towards Industry 4.0 and contribute to a more sustainable world. Because when the current performance is assessed, the next steps for an organization to mature further can be identified.

1.2 Research objective

The aim of this research is two-legged. First, it aims propose a maturity model which assesses the current integration of Industry 4.0 and sustainability of manufacturers. Second, the research aims to validate the scan with feedback from experts.

1.3 Research question

Following up the research objective, the research question is formulated as:

"How can the integration of Industry 4.0 and sustainability of manufacturers be assessed with a maturity model?"

To answer the research question, the following sub-questions are formulated:

- What are aspects of Industry 4.0 that enhance sustainability?
- How can a maturity model be designed to assess the integration of Industry 4.0 and sustainability of a manufacturer?
- How can the developed maturity model be validated?

To answer the research question, the paper is structured as followed. In chapter 2, an extensive literature review is done about the opportunities of sustainability in Industry 4.0, as well as the design of a maturity model. Then, six aspects of sustainability in Industry 4.0 are identified. From this, the Smart Industry Sustainability Scan (SISS) is developed. In chapter 3 and 4, the model is then validated by gathering and analyzing the feedback of experts in Industry 4.0 and sustainability. With the use of the feedback that is presented in chapter 4, the model is improved and the final SISS is presented. To finalize, in chapter 5 the limitations of the research are discussed, recommendations for further research are made, and the research is concluded.

2. LITERATURE REVIEW

2.1 Industry 4.0

Industry 4.0 can be defined as the integration of Cyber-Physical Systems (CPS) and the Internet of Things (IoT) in manufacturing processes. In this way, context-aware Smart Factories are created that assist human and machine with their tasks by making autonomous and decentralized decisions (Hermann et al., 2016). CPS enable the integration of digital and physical systems, where the IoT is the network of objects that are interconnected by smart technologies that enables them to interact (Xia et al., 2012). But besides creating Smart Factories, Industry 4.0 also includes the digitization of distribution channels, value chain members and delivery channels, thereby moving to more service oriented businesses (Schroeder et al., 2019). Industry 4.0 consists of three dimensions of intelligent cross-linking and digitization (Stock & Seliger, 2016). First, the entire value chain network is horizontally integrated. Second, end-to-end engineering is implemented throughout all stages of the product life cycle. And third, all value-creation levels are vertically integrated. Table 1 provides an overview of the relevant smart technologies.

Table 1. Smart technologies

Smart technology	Explanation
Additive Manufacturing (AM)	Technology that produces 3D objects by printing layers on top of each other (Ford & Despeisse, 2016).
Artificial Intelligence (AI)	The programming of machines with human intelligence, enabling machines to learn and solve problems (Lee et al., 2018).
Automated Guided Vehicles (AGV)	Self-driving transport system for the movement of materials (Vis, 2006)
Big Data Analytics	Methods for the analyzation of large and complex data sets, from where systematic information can be extracted (Yan et al., 2017).
Blockchain	Database that stores information in secure and decentralized blocks, that are linked together using cryptography (Bodkhe et al., 2020).
Cloud Computing Cloud Manufacturing	Enables on-demand and reliable computing services.

	Manufacturing resources that can be accessed through cloud services (Xu, 2012).
Cyber-Physical System (CPS)	Intelligent, cross-linked systems that operate autonomous and decentralized by interchanging data (Stock & Seliger, 2016).
Digital Twin (DT)	The virtual version of a physical object, which reflects its status (Scharl & Praktiknjo, 2019).
Internet of Things (IoT)	Enables the connection of physical objects with the Internet (Pereira & Romero, 2017).
Radio Frequency Identification (RFID)	Identification methods that uses radio frequency transmissions (Xiao et al., 2007).
Smart Grid Smart Meter	Electrical grid (interconnected network) that monitors, supervises and adjusts the distribution, generation and consumption of energy (Meng et al., 2018). With the use of e.g. Smart Meters that monitors and communicates data about energy use (Herrmann et al., 2010)
Wireless Sensor Networks (WSN)	Automized, wireless networks of sensors that monitor and communicate data about physical and environmental conditions (Matin & Islam, 2012).

2.2 Sustainability and Industry 4.0

Industrialization has caused an increase in welfare, but has also resulted in negative environmental consequences, which are the impacts of unsustainable consumption and production patterns. Industries are a large contributor to CO2 emission, pollution, scarce raw materials, deforesting, but also poor working conditions and modern slavery practices. Sustainability at the most basic level can be defined as "a characteristic of a process or state that can be maintained indefinitely" (Thayer, 1994, p. 99). This implies that sustainable development means moving from linear to circular processes. The most cited definition of sustainability is retrieved from the Brundtland Report of 1987 by the World Council on Economic Development, where it is defined as: "[development] that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Envrionment and Development, 1987, p. 8). Soon after the Brundtland Report, the term Corporate Social Responsibility (CSR) emerged in management literature. This meant the beginning of a new perspective on business strategy, where the aim is to achieve long-term economic value while regarding environmental and social aspects as well, also referred to as the Triple Bottom Line (Porter & Kramer, 2006). "In manufacturing, sustainability refers to the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources" (Meng et al., 2018, p. 5). Meng et al. argue that sustainability is a core element of smart manufacturing, since Industry 4.0 uses smart technologies to increase efficiency, thereby reducing emission and utilization of raw materials (2018). Manufacturers are forced to look at more sustainable recourses and start recycling since raw material are becoming more and more scarce. Bai et al. argue that the aim of Industry 4.0 technologies is not limited to the economic aspect of business; manufacturers should take their responsibility for the environmental and social aspect as well, in that way addressing societal expectations (2020). From this can be concluded that the pressure for sustainable manufacturing comes from both the inside and the outside. Sustainable development has become a crucial agenda point for manufactures.

2.3 Design of the Smart Industry Sustainability Scan

A maturity model can be used to assess the implementation of Industry 4.0 of organizations to enhance sustainable development. Maturity models can be used as an instrument to conceptualize and measure the readiness or maturity of an organization on a certain aspect (Schumacher et al., 2016). When the current maturity of an organization is determined, the following steps to improve performance can be identified (Fowler, 2014). To answer the research question, a maturity model is proposed. The model contains the following elements: an introduction, the aspects that the scan will measure, the measurement questions per aspect, the answering options, calculation and visualization of the results, and the maturity levels. The SISS complements the Smart Industry Maturity Scan (SIMS) and the extended Smart Industry Maturity Scan (e-SIMS), designed by Luc Ungerer (Ungerer, 2019; Ungerer, 2018). To ensure consistency across the three scans, some elements of the SIMS and e-SIMS are used for the SISS as well. The six aspects naturally emerge from the literature, as well as the measurement questions per aspect. The answering options are ranged from 1 (not at all) to 5 (fully) on a Likert scale. Using an interval scale with equal intervals enables a higher measurement level than nominal, ordinal or ratio scaling. Also, more statistic techniques can be applied to draw conclusions (Burns & Bush, 2005). Because it is possible that not all questions are applicable to an organization, it is also possible to answer n/a, meaning not applicable. When this answer is selected, the question will be removed to get a valid end score. For each aspect, the equal-weighted average is calculated, ranging between 1 and 5. Then, the equal-weighted average of all aspects is calculated, again ranging between 1 and 5. An overview of the attained scores per aspect will be displayed in a radar plot as seen in figure 1, which enables to visualize the scores in a clear way.

Figure 1. Example radar chart of the average score per aspect

The maturity levels of the SIMS and later improved for the e-SIMS are developed by Ungerer (2019). These maturity levels are slightly modified for the SISS. The old levels from level 1 to 5 are: starting implementation, average implementation, semi-advanced leaders, advanced leaders, and expert leaders. Level 1 is referred to as newcomers, level 2 as learners, and level 3, 4 and 5 as leaders. For the levels to be clearer and more consistent, new names are selected. The referring names are left out entirely, as they do not provide more value. From level 1 to 5 the new levels are called: low, low to medium, medium, medium to high, and high integration. Following figure 2, the maturity level can be assigned.

Figure 2. Maturity levels.

Level 1 (1-1,49)	**Low integration**
Level 2 (1,5-2,49)	**Low to medium integration**
Level 3 (2,5-3,49)	**Medium integration**
Level 4 (3,5-4,49)	**Medium to high integration**
Level 5 (4,5-5)	**High integration**

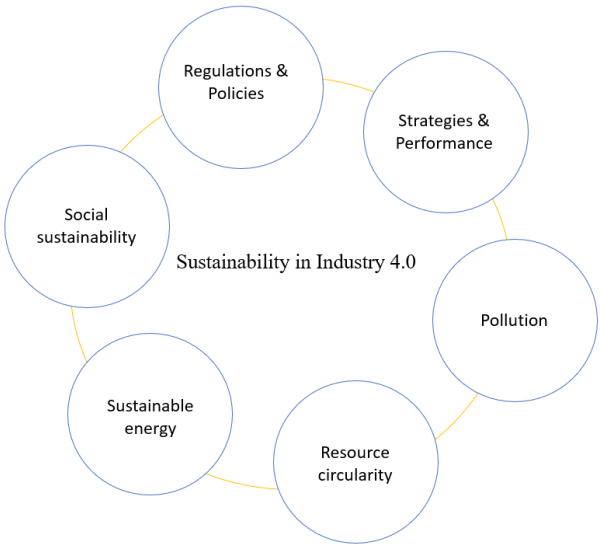
For the formulation of the measurement questions, the following requirements for constructing a questionnaire were taken into account: avoid double-barreled questions, avoid ambiguity, avoid complexity, avoid presuppositions, avoid biases, use simple and clear words, be specific, avoid long questions, make clear and mutually exclusive answer options, make clear, logic and consistent questions, and use a language that is understandable for the reader (Martin, 2006; Nemoto & Beglar, 2014; Siniscalco & Auriat, 2005; Taylor-Powell, 1998; van den Berg & van der Kolk, 2014). To be consistent, almost all questions obtain the following structure: "to what extent has Industry 4.0 – *a verb e.g. 'enabled' or 'supported' – a certain aspect of sustainability*". The use of wording is intentional here. The scan aims to assess the current implementation of Industry 4.0 and sustainability, which is made most clear by using the present perfect tense.

The SIMS does not include sustainability aspects. The e-SIMS does include a sustainability aspect, with five measurement questions. These questions assess the extent to which smart technologies enable: the improvement of environmental sustainability, the implementation of sustainable management strategies, the measurement of sustainability of the products, the measurement of production emissions, and the measurement of emissions from the products in the field (Ungerer, 2019). For a scan that measures the integration of Industry 4.0 and sustainability, the following model is proposed.

2.4 The model: Smart Industry Sustainability Scan

Based on the literature, the following model of the SISS is proposed. Per aspect, smart technologies that can contribute to sustainability are provided, as well as examples of applications. The aspects of sustainability in Industry 4.0 can be found in Figure 3. The complete SISS can be found in appendix A.

Figure 3. The aspects of the SISS.



2.4.1 Regulations & policies

The first aspects of the SISS provides an overview of all regulations and policies that are applicable to the organization, whether they are regional, national or international. On international level the 17 Sustainable Development Goals and the Paris Agreement have been important. In 2015 all United Nations Member States adopted the 17 Sustainable Development Goals, which provide a blueprint for sustainable development for organizations, industries and countries (United Nations). Bai et al. elaborate on how Industry 4.0 technologies have the potential to contribute to all 17 goals (2020). Digitization and smart technologies can for example improve industrial efficiency, transparency in supply chains, and production and consumption patterns. But Industry 4.0 applications can also enable collaboration between different stakeholders, reduce CO2 emission, promote responsibility, and support healthcare and education to name a few. The Paris Agreement, signed by 196 parties at the COP 21 in 2015, is a legally binding treaty on climate change (United Nations). Its aim is to reduce global warming by limiting greenhouse gas emission. The participating countries are asked to develop long-term strategies on greenhouse gas emission, and are supported by a framework of financial, technical and capacity building support in order to realize the goals (United Nations). In the Netherlands there are various laws on for example environment management, waste, water, soil protection, soil energy systems and storage of sustainable energy (Overheid.nl, 2021b). Municipalities in the Netherlands are authorized to make their own policies on sustainability, which results in several sustainability programs in different work fields (Overheid.nl, 2021a). And for different industrial sectors apply different laws (Kamer van Koophandel, 2021). The first step for any organization is to be aware of and comply to the different applicable regulations and policies on sustainability.

a. To what extent does the organization comply to applicable (regional/national/international) regulations regarding sustainable manufacturing?
b. To what extent has Industry 4.0 contributed to the compliment with those regulations?
c. To what extent does the organization comply to applicable (regional/national/international) policies regarding sustainable manufacturing?

d. To what extent has Industry 4.0 contributed to the compliance with those policies?

2.4.2 Sustainable strategy & performance

The second aspect gives an overview of the current strategies and measurements on sustainability. Corporate sustainable is a broad term for balancing both long-term and short-term stakeholder value (Dyllick & Hockerts, 2002). This can be done by implementing a business strategy that aims longevity, transparency and employee development. Examples of sustainable strategies are CSR and Circular Economy. Sustainable management tools can support sustainable strategies. Examples of tools are: eco-efficiency which focuses on creating more value with less environmental resources, life-cycle assessment which considers environmental impacts over the entire life cycle of a product, and product-service systems that include service into business models to enable collaborative consumption (Finnveden et al., 2009; Guenster et al., 2011; Mont, 2002). The sustainable performance of an organization can be measured by means of various tools. Examples are benchmarks, indicators, indices and metrics (Dalal-Clayton & Sadler, 2014). Global sustainability statistics as the UN Environmental Indicators, The International Energy Agency, the Environmental Performance Index can be consulted for this (IEA, 2021; United Nations, 2021; Wendling et al., 2020). But also Life-Cycle Assessment and the Ecological Footprint are often used as sustainability measurement tools (Global Footprint Network, 2021; Ilgin & Gupta, 2010). Auditing, reporting, and accounting methods as ISO 14000, The Natural Step, Triple Bottom Line Accounting, and the Global Reporting Initiative can support and guide organizations to report sustainable performances (Burritt & Christ, 2016; GRI; Holmberg et al., 1999; ISO; Slaper & Hall, 2011). Industry 4.0 technologies can monitor the whole value chain process by providing real-time data (Nagy et al., 2018). This enables to support the implementation of strategies and tools.

Industry 4.0 also provides opportunities for sustainable business model innovation (Müller et al., 2018). To compete, businesses have to innovate their business models to be sustainable (Young & Gerard, 2021). Additive Manufacturing (AM) can repair, refurbishment and remanufacturing products in order to extend the life-span of products, an example of a technology that enables a shift to product-service oriented business models (Ford & Despeisse, 2016). This so called "servitization" is supported by the digital data-centered technologies Industry 4.0 offers, enabling highly individualized and customized solutions (Müller et al., 2018). AM, Cloud Computing and Radio Frequency Identification (RFID) technologies support customization of products, as well made-to-order production (Ford & Despeisse, 2016; Meng et al., 2018). The measurement questions for this aspect are:

a. To what extent has Industry 4.0 enabled the implementation of corporate sustainable strategies?
b. To what extent has Industry 4.0 enabled the implementation of sustainable management tools?
c. To what extent has Industry 4.0 enabled the measurement of sustainable performance?
d. To what extent has Industry 4.0 enabled reporting of sustainable performance?
e. To what extent has Industry 4.0 initiated sustainable business model innovation?

2.4.3 Pollution

Industrial pollution can be broken down by the pollution of water, air and soil (Shen, 1995). For many decades, the disposal of waste in the environment was a "cheap" solution, thereby not assessing environmental and social costs. Recently, attention has been growing for smart sensors in the Industrial Internet of Things, allowing for pollution monitoring (Wan et al., 2020). The most common pollution is the emission of greenhouse gasses into the air, like CO2. Globally, about 50 billion tonnes of greenhouse gasses are emitted every year (Climatewatch, 2021). In the year 2016 for example, the energy use in industries contributed 24.2% and direct industrial processes for 5.2% to total greenhouse emission (Ritchie & Roser, 2020). In general, the optimization of industrial processes caused by the rise of Industry 4.0 lead to a decrease in emissions (Gabriel & Pessl, 2016). More specifically, smart technologies can for example contribute to the decrease in greenhouse gas emission by data-centered traceable carbon footprints (Bai et al., 2020). And smart logistic technologies enable for decentralized and autonomous operation of transportation (Stock & Seliger, 2016). For example, Automated Guided Vehicles (AGV) can realize a material flow inside the building, using identification methods as QR codes and RFID chips. When emission is measured, the next step is emission compensation. Examples of Negative Emission Technologies (NET) that can capture emitted greenhouse gasses are: afforestation and reforestation, bioenergy with carbon capture and storage, direct air capture, and soil carbon sequestration (Haszeldine et al., 2018; Minx et al., 2018). The measurement questions for this aspect are:

a. To what extent has Industry 4.0 enabled the organization to decrease pollution of water?
b. To what extent has Industry 4.0 enabled the organization to decrease pollution of soil?
c. To what extent has Industry 4.0 measured the pollution of air of production processes?
d. To what extent has Industry 4.0 measured the pollution of air of your products in the field?
e. To what extent has Industry 4.0 measured the pollution of air inside the corporate buildings?
f. To what extent has Industry 4.0 enhanced sustainable transport decisions throughout the whole value chain?
g. To what extent has Industry 4.0 enabled for emission compensation?

2.4.4 Resource circularity

Circular Economy is an emerging concept that can help organization move towards sustainable development (de Sousa Jabbour, Jabbour, Godinho Filho, et al., 2018). This can be done by adopting a circular approach to material and energy processes. Two of the main principles of Circular Economy include the optimization of resource productivity using circular products, components and materials processes, and the preservation of natural resources (MacArthur et al., 2015). Optimizing the circularity of materials and resources used in production systems provides a solution for the exhaustion of raw materials. Also, waste products can still be of value for the organization. For this, the R framework is often addressed. The 9R's of Kirchherr include: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover (2017). For the preservation of natural capital, renewable resources should be deployed (de Sousa Jabbour, Jabbour, Godinho Filho, et al., 2018). Smart grid technologies enable effective generation, distribution and controlling of renewable resources (Camacho et al., 2011; Stock & Seliger, 2016). Industry 4.0 also holds opportunities for ecological restoration. Drones, AI, Blockchain and Big Data can be deployed to restore ecosystems, for example reforestation (DGB, 2021). Industry 4.0 can contribute to extent product-life cycles as well, with for example modular design,

customization, and maintenance and repair. With modular designs, product elements are designed to serve a modular purpose: they can be created, exchanged and modified independently (Scharl & Praktiknjo, 2019). This enables for a certain degree of standardization and customization achieved simultaneously. Also, product life-cycles can be extended and the components of products can be recycled, reused and disposed better (Tseng et al., 2008). Modularity enables for a flexible, agile and decentralized production process, and is able to meet dynamic customer needs (Ghobakhloo, 2020). AM facilitates modular design, and CPS can support modular system development (Ford & Despeisse, 2016; Suri et al., 2017). AM, Cloud Computing and RFID technologies support customization of products, as well as made-to-order production, which contributes to resource efficiency (Ford & Despeisse, 2016; Meng et al., 2018). CPS enable manufactures to use accurate customer information for the development of products, and AM enables repair and maintenance opportunities, both resulting in extended product life-cycles (de Sousa Jabbour, Jabbour, Foropon, et al., 2018; Ford & Despeisse, 2016). Last, Industry 4.0 as well as sustainability involve decisions made throughout the whole value chain (Ghobakhloo, 2020). The Digital Supply Chain for example is an integrated network where all functions in the value chain can interact (Büyüközkan & Göçer, 2018).The measurement questions for this aspect are:

a. To what extent has Industry 4.0 optimised resource productivity by using circular products, components, and materials processes?
b. To what extent has Industry 4.0 enabled the preservation of natural resources?
c. To what extent has Industry 4.0 enabled ecological restjoration?
d. To what extent has Industry 4.0 contributed to extend the life cycle of products?
e. To what extent has Industry 4.0 enabled the organization to make sustainable supplier decisions?

2.4.5 Energy efficiency/sustainable energy

In 2018, the industry sector was responsible for 37% of total energy use globally (IEA, 2020). Between 2010 and 2019 energy consumption in this sector increased 0.9% each year. The development of sustainable energy and increasing energy efficiency provide solutions for the negative effects of energy consumption on the environment, as well as the depletion of fossil fuels. Industrial energy productivity has been rising since 2000, among others caused by the gaining influence of smart technologies that aim to facilitate sustainable energy (IEA, 2020; Meng et al., 2018). Industry 4.0 can support renewable energy systems by enabling transparency through the creation of digital twins, increase in flexibility, and enhance energy efficiency (Scharl & Praktiknjo, 2019). Smart grid technologies monitor, supervise and adjust the distribution, generation and consumption of power in order to reduce energy losses and increase the reliability of power supply (Meng et al., 2018). With the use of smart meters that capture for example energy peaks, the energy efficiency of all manufacturing levels can be improved (Herrmann et al., 2010). CPS can plan energy-efficient logistic routes (de Sousa Jabbour, Jabbour, Foropon, et al., 2018). Based on cloud computing, cloud manufacturing is oriented on customer needs and helps to reconstruct resources and schedules to increase energy efficiency (Wu et al., 2013). And Wireless Sensor Networks (WSN) enable IoT devices to harvest energy from surroundings to use for their own operations (Alegret et al., 2019). The measurement questions for this aspect are:

a. To what extent has Industry 4.0 supported renewable energy systems?
b. To what extent has Industry 4.0 improved the performance of energy devices?
c. To what extent has Industry 4.0 contributed to efficient energy systems?
d. To what extent is energy efficiency regarded throughout the whole value chain?

2.4.6 Social sustainability

Besides an economic and environmental aspects, sustainability includes a social aspect as well (Porter & Kramer, 2006). The rise of Industry 4.0 has several consequences for human, which are considered in the last aspect of the scan. First, smart and autonomous production systems have the capability to replace exhausting and repetitive work (Müller et al., 2018). This contributes to human safety and overall employee satisfaction. It also means that the role for human in the factory changes from mechanical labor to labor more focused on conducting and coordinating processes (Gabriel & Pessl, 2016). To meet the requirements of emerging jobs, the need for new skills arises, for example in communication, planning, decision-making, digitization, problem-solving, creativity, teamwork, and self-organization, as well as interdisciplinary knowledge and skills (Gabriel & Pessl, 2016; Kergroach, 2017; Sima et al., 2020). This challenges human to achieve a new level of concurrence between human and machine. For this, the development of human capital for sustainability related matters is required. This can be achieved by the means of education, monitoring and training (Baumgartner & Ebner, 2010; Deaconu et al., 2018). The digitization taking place in Industry 4.0 can support this, as well as cooperation partnerships and the research and development (Sima et al., 2020). Cooperation partnerships enable to organizations to exchange knowledge and resources, where research and development supports sustainable innovations (Stachová et al., 2019). From a consumer perspective, Industry 4.0 enables to optimize product safety, as well as educate about sustainable decisions. AM, the IoT and CPS enable production systems to predict, recognize and solve safety problems, and optimize product quality (Li & Lau, 2017). Besides, the data that is created by digitization provides customers with transparent information about products and processes (Nagy et al., 2018). The transparency of information can contribute to the education of customers as well, supporting sustainable consumer decisions. Last, ethical behavior is crucial when considering social sustainability and an emerging subject of recent times. It regards among others human rights, respect, involvement and consideration of all involved stakeholders (Baumgartner & Ebner, 2010). Modern slavery is an example of this: in 2019 globally 40 million people were exploited, forced, trafficked or abused into work (World Economic Forum, 2019). Besides standards that need to be implemented throughout entire supply chains, smart technologies have the ability to dislocate and counteract modern slavery (Lewin, 2019). In his article, Lewin describes how different organizations make this happen. Blockchains enables to record and preserve transparent information that cannot be corrupted, AI is able to identify trafficking, and machine learning can detect brick kilns that are often populated with forced workers (Lewin, 2019). The measurement questions for this aspect are:

a. To what extent has Industry 4.0 improved human safety?
b. To what extent has Industry 4.0 increased employee satisfaction?
c. To what extent has Industry 4.0 enhanced human capital development?

d. To what extent has Industry 4.0 enabled cooperation partnerships?
e. To what extent has Industry 4.0 supported the research and development of sustainable innovations?
f. To what extent has Industry 4.0 enhanced product safety?
g. To what extent has Industry 4.0 supported sustainable consumer decisions?
h. To what extent has Industry 4.0 enhanced ethical behaviour of the organization?

3. METHODOLOGY

To answer the research question, a model for a maturity model that assesses the integration of Industry 4.0 and sustainability for manufacturers is proposed. This is done though an extended literature review on Industry 4.0, sustainability, and design of maturity models and questionnaires, which resulted in the first pre-designed scan. To validate the research, feedback from experts in the field of Industry 4.0 and sustainability is gathered. This is done in two rounds. The first pre-designed scan consists of 6 aspects and 24 measurement questions. After receiving the feedback of expert 1 during a one-on-one meeting, the scan was adjusted, resulting in the second pre-designed scan. This scan consists of 6 aspects and 39 measurement questions. The second pre-designed scan was then sent to 8 other experts via email. The document sent to them contained the following elements: a general introduction of the scan, a general explanation per aspect, the measurement questions per aspects, and extra information to clarify each question. Two experts requested to provide the feedback during an online one-on-one meeting, the remaining experts sent the feedback to me via email. The feedback of the experts is gathered, analyzed, and implemented into the scan, to improve the maturity model. The first and second pre-designed scan can be found in appendix B. An overview of all the received feedback can be found in appendix C.

4. RESULTS

This section provides a short introduction of each expert, with a summary of their provided feedback. Then the changes that are made to the scan consequently are given. These changes together resulted in the final SISS that is proposed in chapter 2.

4.1 Feedback of experts

A complete overview the feedback can be found in appendix C. In this overview the specific feedback can be found, if it is implemented for the final scan, and reading material that is proposed by the experts as well.

4.1.1 Expert 1

Expert 1 is a consultant on Digital Strategy, Transformation & Innovation, and New Business. The expert provided me with some suggestions for improvement of the first pre-designed scan. In general, the expert thought the aspects were relevant. But, in the expert's opinion, the measurement questions per questions could cover more ground. The scan could be extended by adding more in-depth measurement questions for each aspect. The expert argued that this would contribute to the insight of manufactures about taking the next steps to take following up the scan. To do this, the expert proposed to add more questions related to the value chain and footprint, instead of only focusing on the manufacturing process. The expert advised as well to include more information to support the questions. In this way, the scan can be made as specific as possible. The implemented improvements that resulted from this feedback session resulted in the second pre-designed scan. The following experts provided feedback on the second pre-designed scan.

4.1.2 Expert 2

Expert 2 is a policy scientist and environmentalist, specialized in circular economy, sustainable energy and biobased economy. The expert provided me with insightful feedback, by helping me to look at the scan from the perspective of manufacturing organizations. In general expert 2 questioned if the specific integration of Industry 4.0 and sustainability is already present for manufacturers, especially for the scope that is assessed in the scan. However, the expert thought the six aspects were covering all important factors. Also, the expert thought the scan has a good length. The scan can contribute to raise awareness about how manufactures can be more sustainable, the expert argued. Out of the experts' own experience, many technical organizations are already doing more on sustainability then they realize. With this the expert means that sustainability is often a by-product of resource- and energy-efficiency, something that manufactures are already trying to optimize for decades. The expert argued that for organizations to understand and implement sustainable manufacturing practices, it helps if concepts are recognizable and accessible. A way this can be realized is to change the definition about sustainability in the introduction to be more focused on what manufactures are already doing and how next steps can be taken. In the introduction, it can be emphasized more that the scan aims to give organizations more insights in these next steps as well. Besides, the definition of Industry 4.0 can be more concise, the expert argued. The expert also thought an illustration of all aspects in the introduction will give a good overview of what to expect during the scan. For aspect 1, the expert proposed to change the word awareness to compliance. Namely, compliance to regulations and policies is more relevant to measure than awareness about regulations and policies. Next the expert noticed that for aspect 2, some questions were a bit overlapping. The expert advised to look at the other aspects as well to avoid overlap in questions. Last, the expert mentioned that the SISS would function well as a follow-up of the other scans that IXIA offer. In this way, the general maturity on Industry 4.0 of an organization is assessed first, which is a good starting point for the SISS.

4.1.3 Expert 3

Expert 3 is an engineering doctorate holding professor on Industry 4.0, Factory of the Future and Open Automation. In general, the expert advised to make the scan shorter, so that it would be less time consuming. Besides, the experts proposed to translate the scan to Dutch as well. In that case, the term "Industry 4.0" need to be replaced by "Smart Industry". This term is better recognized and understood by Dutch companies. Further, the expert mentioned that it would be interesting to assess the degree to which organizations realize that sustainability will be an essential aspect of future manufacturing, as well as when that impact is expected to be tangible. The expert explained that the integration of sustainability and Industry 4.0 is not yet realized. Manufactures look at sustainability more as resources and energy matter, that is already seen as solved by the use of for example solar panels. The pricing of CO2 will happen in a few years, which will result in higher cost of materials. Therefore the expert prefers to look at sustainable development for manufactures from the Recycling-ladder, a model that visualizes the different levels of recycling.

4.1.4 Expert 4

Expert 4 is the former CEO of an international company that develops smart and customized low flow fluidics solutions. Currently the expert is a Strategic Business Developer at the same company, focusing on customer relations, partnerships, digitization, and social innovation. To start, Expert 4 thought the base of the scan is good. For that reason, the expert did not

provide feedback on the specific aspects and questions, but rather looked at the scan overall. The most important advice the expert gave me was that given answers on the scan are strongly reliant on the personal interpretation of the person that fills in the scan. The expert noticed that some words can be replaced by other words to fit the context of the sentence better. Besides, there were some mistakes in spelling, or inconsistencies across use of words. Therefore, the expert advised to run an extensive check through the text to make sure it is as clear as possible. Next, the expert pointed out that in the introduction the definitions of the two pillars of the scan, Industry 4.0 and sustainability, are short and simple. This while both concepts are comprehensive and already long known. The expert recommended to make the definitions sharper, so that there is less room for personal interpretations of those concepts. The expert also advised to focus more on the "why?" and "what?" in the introduction. Why should someone make the time to do the scan, and what happens with the results for example. To motivate someone to take the scan, this information should definitely be included the expert explained. Next, the expert advised to give an overview of all the aspects in the introduction, as well as the end. In that way, the person that is doing the scan knows what can be expected. Besides the expert advised to mention why the aspects are chosen. Then, for each aspect the expert pointed out that there is both a general explanation, as well as extra information per question. This repetition suggests that the reader has not understood the general explanation and it makes the document longer than is necessary. Therefore, the expert advised to make the general information per aspect short, strong and complete. Then, the questions can be stated without the extra information. Last, the expert gave me some suggestions for reading material about circular innovation and recovery of nature, which are the start and end point of a process. According to the expert, the sustainability concept is more and more moving towards these points and therefore relevant to implement in the scan.

4.1.5 Expert 5

Expert 5 is an assistant professor on Environmental and Energy Management, and a European coordinator of the Greening of Industry Network. The experts research interests are among others: management of natural resources, product development, circular economy, Corporate Social Responsibility, and social and environmental Life Cycle Assessment. This expert gave me insightful feedback about the contents of the scan. The expert thought de formulation of the questions, and in specific the integration of Industry 4.0 and sustainability, is good. In general, the expert thought the aspects are all important, and the questions clear. For a few aspects and questions the expert made some suggestions. First, the expert proposed to include general questions in the beginning about company size and sector. Different sizes and sectors have different regulations and policies, as well as different funds to invest in certain certifications. For the aspect about pollution, the expert suggested to include a question about the pollution of air indoor as well. For the aspect about resource circularity, the expert mentioned that the second questions about renewable resources needs to be explained clearer. Besides, water as a resource can be mentioned for this aspect more specifically, the expert suggested. For the aspect about social sustainability, the expert advised to explain that the economic part of sustainability is the primary aim of Industry 4.0, and therefore the scan focuses on the ecological and social part of sustainability. Last, the expert suggested to add a question about consumer safety as well as educating consumers on sustainability through for example campaigns.

4.1.6 Expert 6

Expert 6 is Program Manager Circular Economy. In general, the expert thought the scan asks the right questions to assess the effect of smart industry on sustainability. The expert is curious of the causal relationship between circularity and digitization, as well as what companies expect which smart technologies are needed to become circular. For the quality of the response, the expert mentioned that it is important to look at which person to ask inside an organization. Last, the expert is curious about the practical application of the scan.

4.1.7 Expert 7

Expert 7 Is a Consultant in Information Technology and Services Industry. In general, the expert suggested to look more at business drivers of an industry. According to the expert, many companies are not focusing on business drivers. In specific smaller members of value chains are missing opportunities because their activities are not connected to the needs of the manufacturing industry. Besides, the expert mentioned that it would be valuable to assess how a company gains their knowledge, for example through universities, partnerships, or research. This can be easily asked with an open question at the beginning of the scan. Last, the expert noted that for the scan to be understandable, it is important to use a language that is accessible for every reader.

4.1.8 Expert 8

Expert 8 is the CEO of a bed manufacturer. The expert thought the scan looks comprehensive and professional. But the expert thinks there lies a challenge in how to make an useful, practical tool out of it. Decision-making regarding strategy and its implementation is often influenced by other factors as well, for example gut feeling and experience. Last, the expert suggests making a distinction in the questions between internal and external factors.

4.2 Implemented feedback

The above feedback of the experts is gathered an analyzed. Then the feedback is implemented to create the final SISS, which can be found in appendix A. An overview of all feedback and whether it is implemented can be found in appendix C. To summarize, the consistency, conciseness and clearness of words are regarded as important by the expert. Besides, useful recommendations are made to improve the introduction. The set of aspects are perceived as relevant and complete by the experts. For every aspect expect aspect five, substantial and useful feedback is received as well.

For the improvement of the second pre-designed scan the following changes are made. In general, spelling and consistency of word use is checked. Overlapping questions are reduced to one question per concept. The general information per aspects is adjusted to be more concise. There is also more focus on why the aspects are chosen. In the beginning of the scan, seven open questions are added, aiming to provide general information about the organization. Six of these questions are also a part of the SIMS and e-SIMS and are added to ensure consistency across the scans. The questions ask for the reference, company name, turnover, number of employees, department of the company, and name of the interviewer. For the seventh open question, the sector the manufacturer operates in is added.

For the introduction, the definition of sustainability is changed to a definition of sustainable manufacturing. In this way, the definition is more recognizable for manufacturers and there is more focus on what they are already doing, namely optimizing production processes. To the introduction is added why it is important to take scan, as well as that the results of the scan aim

to give insight into the next steps to take for the organization. An image of the aspects is added to the introduction to give an overview of what to expect during the scan. For aspect 1, the questions about awareness of regulations and policies are changed to compliance with regulations and policies, since this information is more relevant to assess. For aspect 2, the question about strategic change and the question about business model change are merged into a question about sustainable business model innovation. For aspect three, a question about the pollution of air inside corporate buildings is added. For aspect 4, the question about the preservation of natural capital is clearer formulated. Besides, a question about ecological restoration is added. The question about the 3R model is updated to the 9R model. For aspect 6, questions about product safety and sustainable education are added.

The finale SISS will be translated to Dutch. Both scans will then be programmed and linked to a digital dashboard. Here the results of the scan can be found, as well as additional explanation. The scan is available for companies to take on ixiasmartinsights.nl.

5. DISCUSSION

In this section, limitations are discussed, recommendations for further research are made, and the research is concluded. Last, an acknowledgement is included.

5.1 Recommendations

In this section, the theoretical as well as the practical recommendations of this research are discussed.

5.1.1 Theoretical recommendations

The theoretical contribution of this research is a maturity model that assesses the integration of Industry 4.0 and sustainability. Sustainability has been linked as an opportunity for Industry 4.0, but the assessment of the combination of both aspects in a maturity model is unique. This research provides an overview of the Industry 4.0 applications that enhance sustainable manufacturing. For further research, it is important to stay informed about new developments in Industry 4.0, and how they can contribute to sustainable manufacturing. Promising technologies are being developed, for example for ecological restoration, negative emission technologies, and renewable energies. But also unexplored areas can become theoretically relevant to add to the maturity model. To identify practical next steps for organizations to mature further in the integration of Industry 4.0 and sustainability, insights are needed in the barriers and critical success factors for the implementation of Industry 4.0 as well.

5.1.2 Practical recommendations

The practical contribution of this research is the Smart Industry Sustainability Scan, that can be used to assess the maturity of manufactures on the integration of Industry 4.0 to enhance sustainability. The scan will be offered by IXIA insights. For further research, practical application of the scan is recommended. In this way, it can be assessed if the san is accessible and relevant for organizations. The initial motive behind Industry 4.0 is one of economic nature. But as seen in this research, the aims of Industry 4.0 already contribute to the ecological and social aspect of sustainability as well. Because the integration of both aspects will probably not be fully present for most organization, more research needs to be done on how manufactures can mature further in sustainable manufacturing by implementing Industry 4.0. In order to do so, the barriers and critical success factors for implementing Industry 4.0 to enhance sustainable manufacturing need to be identified. From there, a plan of action can be made for the next steps to take. When the integration of smart technologies enhancing sustainable manufacturing in organizations is more mature, the scan can be extended with the use of practical experiences and insights. The last practical recommendation is to use the SISS as a sequential scan after the SIMS or e-SIMS. In this way the maturity of the implementation of Industry 4.0 is already assessed. From there, the integration with sustainability is a logical next step.

5.2 Limitations

Due to time restrictions, the SISS has not been assessed by an organization. Therefore, one of the limitations is the lack of practical application of the scan. To be clear and understandable, accessible words and concept are used for the scan. But to validate this, feedback about the application of the scan to organizations needs to be gathered. Further, from the feedback of the experts it became clear that the integration of Industry 4.0 and sustainability is still in an early phase. For this reason, the scan remained concise, covering the most important aspects. Many organizations are probably already implementing smart technologies, as well as sustainability concepts, but the integration of both aspects is yet to be realized. Therefore, the scan serves both as a maturity model as well as an overview of the opportunities Industry 4.0 holds for sustainable manufacturing.

5.3 Conclusion

In this research, a Smart Industry Sustainability Scan is designed, to answer the research question: *"How can the integration of Industry 4.0 and sustainability of manufacturers be assessed with a maturity model?"* For the development of the SISS, first an extensive literature review is done about the opportunities of sustainability in Industry 4.0, as well as the design of a maturity model. During the literature review, six aspects of sustainability in Industry 4.0 were identified, namely: Regulations and policies, Strategies and performance, Pollution, Resource circularity, Sustainable energy, and Social sustainability. From these aspects the scan has been further developed. The measurement questions were set up and the answering options and maturity levels were developed. The designed model is then validated by gathering and analyzing the feedback of experts in Industry 4.0 and sustainability. With the use of the feedback, the maturity model is improved and the final SISS is presented. The scan will be programmed and linked to a digital dashboard, where insights into obtained results can be seen. Moreover, IXIA insights will use the dashboard to provide advice about the next step manufactures can take to improve their maturity on the integration of Industry 4.0 and sustainability.

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7. APPENDICES

7.1 Appendix A: Smart Industry Sustainability Scan

Welcome to the Smart Industry Sustainability Scan. This scan assesses the maturity of smart technologies that enhance sustainability of a manufacturing organization. The maturity model provides insight into the current integration of Industry 4.0 and sustainability of your organization. This insight is crucial for any manufacturing organization to compete in the rapidly changing industrial dynamics. From the results, the next steps for your organization to mature on Industry 4.0 and sustainability can be identified together with IXIA smart insights.

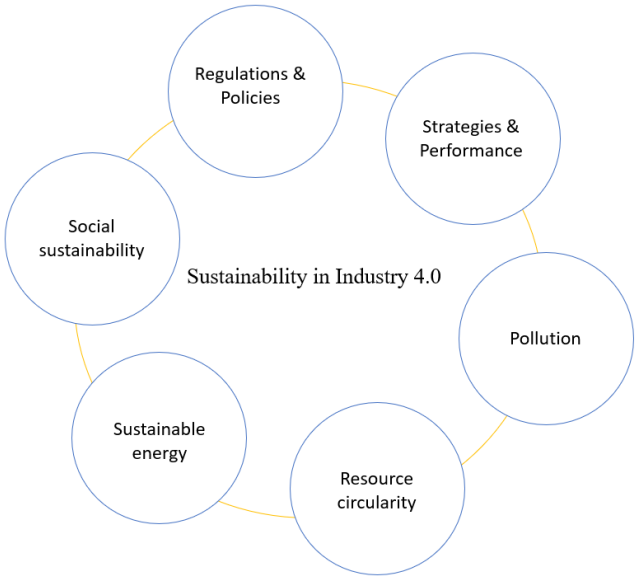
For each question, you can choose an answer from 1 to 5: (1) Not at all, (2) to some extent, (3) semi-advanced, (4) advanced, or (5) fully. Or, if a question is not applicable to the organization, you can answer n/a (not applicable).

In the scan, the term "Industry 4.0" is used, which can be used interchangeably with the term "smart industry" or "smart manufacturing". Industry 4.0 is defined as the integration of Cyber-Physical Systems (CPS) and the Internet of Things (IoT) in manufacturing processes. In this way, context-aware Smart Factories are created that assist human and machine with their tasks by making autonomous and decentralized decisions. CPS enable the integration of digital and physical systems, where the IoT is the network of objects that are interconnected by smart technologies as sensors that enables them to interact.

Sustainable manufacturing involves manufacturing products while minimizing the negative impacts on the environment by preserving resources and energy, by for example moving to circular processes. Industry 4.0 aims to optimize production processes by optimizing resource and energy efficiency by using digitization and smart technologies. And while the initial motive behind Industry 4.0 is of economic nature, Industry 4.0 creates many opportunities for the development of ecological and social sustainability as well.

Six aspects are chosen so that all important aspects of Industry 4.0 in sustainable manufacturing are covered. The aspects are:

Taking the scan will approximately take 1 to 2 hours. It is possible to pause the scan and continue another time.



General information

Reference:

Company name:

Turnover:

Number of employees:

Sector:

Department:

Name interviewer:

1. Regulations & policies

This aspect provides an overview of all regulations and policies that are applicable to the organization, whether they are regional, national or international. On international level the 17 Sustainable Development Goals and the Paris Agreement for example have been important. In the Netherlands there are various laws on for example environment management, waste, water, soil protection, soil energy systems and storage of sustainable energy. Municipalities in the Netherlands are authorized to make their own policies on sustainability, which results in several sustainability programs in different work fields. For any organization it is important to comply to the different applicable rules, regulations, policies and guidelines, as well as how Industry 4.0 can support compliance with those regulation and policies.

Please answer the following questions:

a. To what extent does the organization comply to applicable (regional/national/international) regulations regarding sustainable manufacturing?
b. To what extent has Industry 4.0 contributed to the compliment with those regulations?
c. To what extent does the organization comply to applicable (regional/national/international) policies regarding sustainable manufacturing?
d. To what extent has Industry 4.0 contributed to the compliance with those policies?

2. Strategies & performance

This aspect gives an overview of the current strategies and measurements of performance on sustainability. Corporate sustainable strategies aim to balance both long-term and short-term stakeholder value. Sustainable management tools can support sustainable strategies. Sustainable performance can be measured by means of various tools. Industry 4.0 technologies can monitor the whole value chain process by providing real-time data, which enables to support the implementation of these strategies and tools. Industry 4.0 also provides opportunities for sustainable business model innovation. To compete, businesses have to innovate their business models to be sustainable, which can be realized by Industry 4.0 applications.

Please answer the following questions:

a. To what extent has Industry 4.0 enabled the implementation of corporate sustainable strategies? (i: e.g. Corporate Social Responsibility, Circular economy)
b. To what extent has Industry 4.0 enabled the implementation of sustainable management tools? (i: e.g. eco-efficiency, life-cycle assessment, product-service systems)
c. To what extent has Industry 4.0 enabled the measurement of sustainable performance? (i: e.g. benchmarks, indicators, indices, metrics, as the Global sustainability statistics, the UN Environmental Indicators, The International Energy Agency, and the Environmental Performance Index)
d. To what extent has Industry 4.0 enabled reporting of sustainable performance? (i: e.g. auditing, reporting and accounting methods as ISO 14000 or the Global Reporting Initiative)
e. To what extent has Industry 4.0 initiated sustainable business model innovation? (i: e.g. servitization, customization, repair and maintenance, and made-to-order production)

3. Pollution

Industries are a large contributor to pollution. Industrial pollution can be broken down by the pollution of water, air and soil. The most common pollution is the emission of greenhouse gasses into the air, like CO2. Recently, attention has been growing for smart technologies as sensors to monitor pollution. Smart technologies can for example contribute to a decrease in greenhouse gas emission by the implementation of data-centered traceable carbon footprints. And smart logistic technologies enable for decentralized and autonomous operation of transportation. The whole value chain needs to be considered for sustainable transport. And last, when emission is measured, emission compensation technologies can capture previous emitted greenhouse gasses.

Please answer the following questions:

a. To what extent has Industry 4.0 enabled the organization to decrease pollution of water? (i: e.g. disposal of plastic)
b. To what extent has Industry 4.0 enabled the organization to decrease pollution of soil? (i: e.g. disposal of industrial by-products)
c. To what extent has Industry 4.0 measured the pollution of air of production processes? (i: e.g. emission of greenhouse gas emissions caused by the burning of fossil fuels and biomass)
d. To what extent has Industry 4.0 measured the pollution of air of your products in the field? (i: e.g. the emission of greenhouse gases of manufactured vehicles)
e. To what extent has Industry 4.0 measured the pollution of air inside the corporate buildings? (i: e.g. inside the factory)
f. To what extent has Industry 4.0 enhanced sustainable transport decisions throughout the whole value chain (i: e.g. transport of employees, transportation of materials or products)
g. To what extent has Industry 4.0 enabled for emission compensation? (i: e.g. afforestation and reforestation, bioenergy with carbon capture and storage, direct air capture, and soil carbon sequestration)

4. Resource circularity

Circular Economy is an emerging concept that can help organization to move towards sustainable development. When adopting a circular approach to material processes, resource efficiency can be optimized. This provides a solution for the exhaustion of raw materials. Also, waste products can still retain value. Two of the main principles of Circular Economy include the

optimization of resource productivity using circular products, components and materials processes, and the preservation of natural resources. By making products modular and customized, product life cycles can be extended and components of products can be recycled, reused and disposed better. Additive Manufacturing, Cloud Computing and RFID technologies support customization of products, as well made-to-order production, which contributes to resource efficiency. CPS enable manufactures to use accurate customer information for the development of products, and AM enables repair and maintenance opportunities, both resulting in extended product life cycles. Industry 4.0, as well as sustainability involves decisions made throughout the whole value chain. The Digital Supply Chain for example is an integrated network where all functions in the value chain can interact.

Please answer the following questions:

a. To what extent has Industry 4.0 optimised resource productivity by using circular products, components, and materials processes? (i: e.g. by applying the R-ladder: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover)
b. To what extent has Industry 4.0 enabled the preservation of natural resources? (i: e.g. by using renewable resources, whose supply can be sustained long-term)
c. To what extent has Industry 4.0 enabled ecological restoration? (i: e.g. reforestation with the use of Drones, AI, Blockchain and Big Data)
d. To what extent has Industry 4.0 contributed to extend the life cycle of products? (i: e.g. customization, predictive maintenance, increased quality, modularity)
e. To what extent has Industry 4.0 enabled the organization to make sustainable supplier decisions? (i: e.g. The Digital Supply Network where all functions in the value chain can interact)

5. Sustainable energy

Industries are a large contributor to global energy use. The development of sustainable energy and energy efficiency provides solutions for the negative effects of energy consumption on the environment, as well as the depletion of fossil fuels. Industrial energy productivity has been rising since 2000, among others caused by the gaining influence of smart technologies that aim to facilitate sustainable energy. Industry 4.0 can support renewable energy systems by: enabling transparency through the creation of digital twins, increase in flexibility, and enhance energy efficiency. Smart grids provide many opportunities to improve the performance of energy devices, as well as increase the efficiency of energy systems. Last, energy efficiency needs to be considered throughout the whole value chain.

Please answer the following questions:

a. To what extent has Industry 4.0 supported renewable energy systems? (i: e.g. by proving transparency with digital twins, or increased flexibility)
b. To what extent has Industry 4.0 improved the performance of energy devices? (i: e.g. smart grid technologies that reduce energy losses and increase the reliability of power supply)
c. To what extent has Industry 4.0 contributed to efficient energy systems (i: e.g. by the integration of machines, Wireless Sensor Networks that harvest and reusing energy, data mining which enables the optimization of operation process, product quality and fault recognition, CPS can plan energy-efficient logistic routes, cloud manufacturing is oriented on customer needs and helps to reconstruct resources and schedules to increase energy efficiency)
d. To what extent is energy efficiency regarded throughout the whole value chain (i: e.g. of suppliers)

6. Social sustainability

The rise of Industry 4.0 has several consequences for the social aspect of sustainability as well. Smart and autonomous production systems have the capability to replace exhausting and repetitive work, contributing to human safety and employee satisfaction. The role for human in the factory changes as well to be more conducting and coordinating. To meet the requirements of emerging jobs, the need for new skills arises, causing job enrichment. For this he development of human capital for sustainability related matters should be considered. This can be done through education, training and monitoring. The digitization taking place in Industry 4.0 can support this, as well as cooperation partnerships and the research and development. Cooperation partnerships enable to organizations to exchange knowledge and resources, where research and development supports sustainable innovations. From a consumer perspective, Industry 4.0 enables to optimize product safety, as well as educate about sustainable decisions. Last, ethical behavior is crucial when considering social sustainability and an emerging subject of recent times. It regards among others human rights, respect, involvement and consideration of all involved stakeholders.

Please answer the following questions:

a. To what extent has Industry 4.0 improved human safety? (i: e.g. the automation of unsafe and exhausting activities)

b. To what extent has Industry 4.0 increased employee satisfaction? (i: e.g. the replacement of boring and exhausting work, job enrichment)
c. To what extent has Industry 4.0 enhanced human capital development? (i: e.g. learning, but also experimenting, involvement of employees, motivating employees)
d. To what extent has Industry 4.0 enabled cooperation partnerships? (i: e.g. members in the value chain, other organizations, learning)
e. To what extent has Industry 4.0 supported the research and development of sustainable innovations? (i: e.g. experimenting, doing research, sustainable innovation)
f. To what extent has Industry 4.0 enhanced product safety? (i: e.g. production systems that predict, recognize and solve safety problems, and optimize product quality)
g. To what extent has Industry 4.0 supported sustainable consumer decisions? (i: e.g. through campaigns, transparency of corporate information)
h. To what extent has Industry 4.0 enhanced ethical behaviour of the organization? (i: e.g. dislocate and counteract modern slavery practices)

Thank you for filling in the Smart Industry Sustainability Scan. With the results, insight into the integration of Industry 4.0 and sustainability is provided, specifically on the following aspects: Regulations & Policies, Strategies & Performance, Pollution, Resource Circularity, Sustainable Energy, and Social Sustainability.

For further questions you can contact IXIA smart insights.

7.2 Appendix B: The pre-designed scans

7.2.1 Pre-designed scan 1

Welcome to the SISS scan. This scan assesses the maturity of smart technologies inside your organization that contribute to sustainability. For each question, you can choose an answer from 1 to 5: (1) Not at all, (2) to some extent, (3) advanced, (4) semi advanced, and (5) fully.

In the scan, the term “Industry 4.0” is used, which can be used interchangeably with the term “smart industry”, “smart technologies” or “smart manufacturing”. The term “sustainability” is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In the scan the economic, ecological and social aspects of sustainability are considered.

It is possible to pause the scan and continue another time.

1. Regulations and policies

This aspect provides an overview of all regulations and policies that are applicable to the organization, whether they are regional, national or international. Regulations and policies on sustainability differ in countries and regions. For any organization it is important to be aware of the different applicable rules, regulations, policies and guidelines, as well as how Industry 4.0 can help to comply to those rules and policies. Please answer the following questions:

a. To what extent is the organization aware of the applicable (regional/national/international) regulations regarding sustainable manufacturing?
b. To what extent has Industry 4.0 contributed to the compliment with those regulations?
c. To what extent is the organization aware of the applicable (regional/national/international) policies regarding sustainable manufacturing?
d. To what extent has Industry 4.0 contributed to the compliment with those policies?

2. Sustainable strategies and performance

This aspect gives an overview of the current strategies and measurements on sustainability. Corporate sustainable strategies aim to balance both long-term and short-term stakeholder value. Examples of such strategies can be Corporate Social Responsibility and Circular Economy. Sustainable management tools can support sustainable strategies. Examples of tools are eco-efficiency and life-cycle assessment. Strategic change is also recognized in Industry 4.0; business models move for example to be more product-service oriented. This movement is supported by the digital data-centered technologies Industry 4.0 offers, enabling highly individualized and customized solutions. Sustainable performance can be measured by means of various tools. Examples are benchmarks, indicators, indices, metrics, auditing and reporting. Please answer the following questions:

a. To what extent has Industry 4.0 enabled the implementation of corporate sustainable strategies? (e.g. Corporate Social Responsibility, Circular economy)
b. To what extent has Industry 4.0 enabled the implementation of sustainable management tools? (e.g. eco-efficiency, life-cycle assessment, product-service systems)
c. To what extent has Industry 4.0 initiated strategic change of business models?
d. To what extent has Industry 4.0 enabled the measurement of sustainable performance? (e.g. benchmarks, indicators, indices, metrics, auditing and reporting)

3. Emission pollution

Industries are a large contributor to pollution. Industrial pollution can be broken down by the pollution of water, air and soil. Recently, attention has been growing for smart technologies as sensors to monitor as well as decrease pollution. The most common pollution is the emission of greenhouse gasses into the air, like CO2. Please answer the following questions:

a. To what extent has Industry 4.0 enabled the organization to decrease pollution of water? (e.g. disposal of plastic)
b. To what extent has Industry 4.0 enabled the organization to decrease pollution of soil? (e.g. disposal of industrial by-products)
c. To what extent has Industry 4.0 measured the pollution of air of production processes? (e.g. emission of greenhouse gas emissions caused by the burning of fossil fuels and biomass)
d. To what extent has Industry 4.0 measured the pollution of air of your products in the field? (e.g. the emission of greenhouse gases of manufactured vehicles)

4. Resource circularity

Circular Economy is an emerging concept that can help organization to move towards sustainable development. When adopting a circular approach to material processes, resource efficiency can be optimized. This provides a solution for the exhaustion of raw materials. Also, waste products can still retain value. For resource circularity the concept of the three 3R's (recycle, reuse and reduce) are often addressed. Please answer the following questions:

a. To what extent has Industry 4.0 enabled the organization to apply the 3R's? (recycle, reuse, reduce)
b. To what extent has Industry 4.0 enabled the preservation of natural capital (by creating a balance of consumption between renewable and non-renewable resources)?
c. To what extent has Industry 4.0 optimised resource productivity by using circular products, components, and materials processes?
d. To what extent has Industry 4.0 enabled the reduction of the negative effects of production systems on human welfare?

5. Sustainable energy

Industries are a large contributor to global energy use. The development of sustainable energy and energy efficiency provides solutions for the negative effects of energy consumption on the environment, as well as the depletion of fossil fuels. Industrial energy productivity has been rising since 2000, among others caused by the gaining influence of smart technologies that aim to facilitate sustainable energy. Please answer the following questions:

a. To what extent has Industry 4.0 enabled the generation of renewable energy?
b. To what extent has Industry 4.0 improved the performance of energy devices? (e.g. energy production devices or energy store devices)
c. To what extent has Industry 4.0 contributed to efficient energy systems (e.g. integration of machines, monitoring, decision-making or modelling)
d. To what extent has Industry 4.0 optimized operation processes?

6. Social sustainability

The rise of Industry 4.0 has several consequences for the social aspect of sustainability as well. Smart and autonomous production systems have the capability to replace exhausting and repetitive work, contributing to human safety and employee satisfaction. The role for human in the factory changes as well to be more conducting and coordinating. In order to meet the requirements of emerging jobs, the need for new skills arises, causing job enrichment. The rise of Industry 4.0 challenges human to achieve a new level of concurrence between human and machine. For this he development of human capital for sustainability related issues should be considered, which can be done through education, training and monitoring. Besides, ethical behavior is an emerging domain of recent times. It regards among others human rights, and the involvement and consideration of all involved stakeholders. Smart technologies have for example the ability to contribute to dislocate and counteract modern slavery practices. Please answer the following questions:

a. To what extent has Industry 4.0 improved human safety? (by e.g. the automation of unsafe and exhausting activities)
b. To what extent has Industry 4.0 increased employee satisfaction? (by e.g. the replacement of boring and exhausting work, job enrichment)
c. To what extent has Industry 4.0 encouraged human capital development?
d. To what extent has Industry 4.0 improved the ethical behaviours of the organization?

Thank you for filling in the Smart Industry Sustainability Scan. For further questions you can contact us.

7.2.2 Pre-designed scan 2

Welcome to the Smart Industry Sustainability Scan. This scan assesses the maturity of smart technologies that enhance sustainability of a manufacturing organization. For each question, you can choose an answer from 1 to 5: (1) Not at all, (2) to some extent, (3) advanced, (4) semi advanced, or (5) fully. Or, if a question is not applicable to the organization, you can answer n/a.

In the scan, the term "Industry 4.0" is used, which can be used interchangeably with the term "smart industry", "smart technologies" or "smart manufacturing". Industry 4.0 is defined as the integration of Cyber-Physical Systems and the Internet of Things in manufacturing processes. In this way, context-aware Smart Factories are created that assist human and machine with their tasks by making autonomous and decentralized decisions. Cyber-Physical

Systems enable the integration of digital and physical systems, where the Internet of Things is the network of objects that are interconnected by smart technologies as sensors that enables them to interact.

The term “sustainability” is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In the scan the economic, ecological, and social aspects of sustainability are considered.

It is possible to pause the scan and continue another time.

1. Regulations and policies

This aspect provides an overview of all regulations and policies that are applicable to the organization, whether they are regional, national or international. On international level, the 17 Sustainable Development Goals and the Paris Agreement are examples of regulations and policies on sustainability. Regulations and policies differ across countries and regions but are all to a certain extent influenced by international laws and guidelines. In the Netherlands there are various laws on for example environment management, waste, water, soil protection, soil energy systems and storage of sustainable energy. Municipalities in the Netherlands are authorized to make their own policies on sustainability, which results in several sustainability programs in different work fields. For any organization it is important to be aware of the different applicable rules, regulations, policies and guidelines, as well as how Industry 4.0 can support compliance with those regulation and policies.

Please answer the following questions:

a. To what extent is the organization aware of the applicable (regional/national/international) regulations regarding sustainable manufacturing? (i: a regulation is an authoritative rule)
b. To what extent has Industry 4.0 contributed to the compliment with those regulations? (e.g. digitization and smart technologies can improve industrial efficiency, transparency in supply chains, and production patterns)
c. To what extent is the organization aware of the applicable (regional/national/international) policies regarding sustainable manufacturing? (a policy is guideline that is ought to be followed)
d. To what extent has Industry 4.0 contributed to the compliance with those policies?

2. Sustainable strategies and performance

This aspect gives an overview of the current strategies and measurements on sustainability. Corporate sustainable strategies aim to balance both long-term and short-term stakeholder value. Examples of such strategies can be Corporate Social Responsibility and Circular Economy. Sustainable management tools can support sustainable strategies. Examples of tools are eco-efficiency and life-cycle assessment. Strategic change is also recognized in Industry 4.0; business models move for example to be more product-service oriented. This movement is supported by the digital data-centered technologies Industry 4.0 offers, enabling highly individualized and customized solutions. Sustainable performance can be measured by means of various tools. Examples are benchmarks, indicators, indices, metrics, auditing and reporting. Industry 4.0 also provides opportunities for innovation of both emerging and established business models. Smart technologies hold the ability for servitization, customization and made-to-order production. Lastly, Industry 4.0, as well as sustainability involves decisions made throughout the whole value chain. Therefore decisions regarding suppliers, partners and customers should be considered for sustainable development.

Please answer the following questions:

a. To what extent has Industry 4.0 enabled the implementation of corporate sustainable strategies? (e.g. Corporate Social Responsibility, Circular economy)
b. To what extent has Industry 4.0 enabled the implementation of sustainable management tools? (e.g. eco-efficiency, life-cycle assessment, product-service systems)
c. To what extent has Industry 4.0 enabled the measurement of sustainable performance? (e.g. benchmarks, indicators, indices, metrics, e.g. Global sustainability statistics as the UN Environmental Indicators, The International Energy Agency, the Environmental Performance Index)
d. To what extent has Industry 4.0 enabled reporting of sustainable performance? (e.g. auditing, reporting and accounting methods)
e. To what extent has Industry 4.0 initiated a strategic change enhancing sustainability? (e.g. chance in business model to be more service oriented, in that way expanding the life-span of products)
f. To what extent has Industry 4.0 contributed to servitization? (e.g. repair and maintenance to extent product life-span, or offering advice for customers regarding sustainable decisions)
g. To what extent has Industry 4.0 supported sustainable decisions throughout the whole value chain? (e.g. suppliers, partners, but also own buildings, transportation, food, ect.)

3. Emission pollution

Industries are a large contributor to pollution. Industrial pollution can be broken down by the pollution of water, air and soil. The most common pollution is the emission of greenhouse gasses into the air, like CO2. Recently, attention has been growing for smart technologies as sensors to monitor as well as decrease pollution. Specifically, smart technologies can for example contribute to a decrease in greenhouse gas emission by the implementation of data-centered traceable carbon footprints.

Please answer the following questions:

a. To what extent has Industry 4.0 enabled the organization to reduce overall waste? (by e.g. improving product quality, recycling, resource efficiency, modularity)
b. To what extent has Industry 4.0 enabled the organization to decrease pollution of water? (e.g. disposal of plastic)
c. To what extent has Industry 4.0 enabled the organization to decrease pollution of soil? (e.g. disposal of industrial by-products)
d. To what extent has Industry 4.0 measured the pollution of air of production processes? (e.g. emission of greenhouse gas emissions caused by the burning of fossil fuels and biomass)
e. To what extent has Industry 4.0 measured the pollution of air of your products in the field? (e.g. the emission of greenhouse gases of manufactured vehicles)
f. To what extent has Industry 4.0 enabled more sustainable transport decisions throughout the whole value chain (e.g. transport of employees, transportation of materials or products)
g. To what extent has Industry 4.0 enabled for emission compensation?

4. Resource circularity

Circular Economy is an emerging concept that can help organization to move towards sustainable development. When adopting a circular approach to material processes, resource efficiency can be optimized. This provides a solution for the exhaustion of raw materials. Also, waste products can still retain value. For resource circularity the concept of the three 3R's (recycle, reuse and reduce) is often addressed. The main principles of Circular Economy include: 1) preservation of natural capital; 2) optimization of resource productivity using circular of products, components, and materials processes; and 3) reduction of the negative effects of production systems on human welfare. By making product modular and customized, product life cycles can be extended and components of products can be recycled, reused and disposed better. Additive Manufacturing, Cloud Computing and RFID technologies support customization of products, as well made-to-order production, which contributes to resource efficiency. And Additive Manufacturing enables repair and maintenance opportunities, as well contributing to extended product life cycles.

Please answer the following questions:

a. To what extent has Industry 4.0 enabled the organization to apply the 3R's? (recycle, reuse, reduce)
b. To what extent has Industry 4.0 enabled the preservation of natural capital (by creating a balance of consumption between renewable and non-renewable resources)?
c. To what extent has Industry 4.0 optimised resource productivity by using circular products, components, and materials processes?
d. To what extent has Industry 4.0 enabled the reduction of the negative effects of production systems on human welfare?
e. To what extent has Industry 4.0 enabled modularity? (with modular design, product elements are designed to serve a modular purpose: they can be created, exchanged and modified independently)
f. To what extent has Industry 4.0 enabled customization of products?
g. To what extent has Industry 4.0 enabled the organization to make sustainable supplier decisions?
h. To what extent has Industry 4.0 contributed to extend the life cycle of products? (e.g. predictive maintenance, increased quality)

5. Sustainable energy

Industries are a large contributor to global energy use. The development of sustainable energy and energy efficiency provides solutions for the negative effects of energy consumption on the environment, as well as the depletion of fossil fuels. Industrial energy productivity has been rising since 2000, among others caused by the gaining influence of smart technologies that aim to facilitate sustainable energy. Smart grid technologies monitor, supervise and adjust the distribution, generation and consumption of power in order to reduce energy losses and increase the reliability of power supply. Data mining enables the optimization of operation process, product quality and fault recognition. CPS can plan energy-efficient logistic routes and cloud manufacturing is oriented on customer needs and helps to reconstruct resources and schedules to increase energy efficiency and decrease production costs. With Additive Manufacturing, the time between design and production can be reduced significantly, and so the use of energy, in that way contributing to energy efficiency.

Please answer the following questions:

a. To what extent has Industry 4.0 enabled the generation of renewable energy?
b. To what extent has Industry 4.0 improved the performance of energy devices? (e.g. energy production devices or energy store devices)
c. To what extent has Industry 4.0 contributed to efficient energy systems (e.g. integration of machines, monitoring, decision-making or modelling, capturing and reusing heat or water)
d. To what extent has Industry 4.0 optimized operation processes?
e. To what extent has Industry 4.0 enabled energy neutral design? (the design of e.g. products or processes where energy efficiency is considered in every step of planning and production, this can be done for example by designing devices that are environmentally powered, e.g. by the sun)
f. To what extent is energy efficiency regarded throughout the whole value chain (e.g. of suppliers)

6. Social sustainability

The rise of Industry 4.0 has several consequences for the social aspect of sustainability as well. Smart and autonomous production systems have the capability to replace exhausting and repetitive work, contributing to human safety and employee satisfaction. The role for human in the factory changes as well to be more conducting and coordinating. In order to meet the requirements of emerging jobs, the need for new skills arises, causing job enrichment. The rise of Industry 4.0 challenges human to achieve a new level of concurrence between human and machine. For this he development of human capital for sustainability related issues should be considered, which can be done through education, training and monitoring. Besides, ethical behavior is an emerging domain of recent times. It regards among others human rights, and the involvement and consideration of all involved stakeholders. Smart technologies have for example the ability to contribute to dislocate and counteract modern slavery practices. Industry 4.0 also holds opportunities for cooperation partnerships, research and development and corporate citizenship.

Please answer the following questions:

a. To what extent has Industry 4.0 improved human safety? (by e.g. the automation of unsafe and exhausting activities)
b. To what extent has Industry 4.0 increased employee satisfaction? (by e.g. the replacement of boring and exhausting work, job enrichment)
c. To what extent has Industry 4.0 enhanced human capital development? (e.g. learning, but also experimenting, involvement of employees, motivating employees)
d. To what extent has Industry 4.0 improved the ethical behaviours of the organization?
e. To what extent has Industry 4.0 enabled cooperation partnerships? (e.g. members in the value chain, other organizations, learning, experimenting and doing research)
f. To what extent has Industry 4.0 supported the research and development of sustainable innovations?
g. To what extent has Industry 4.0 enabled for corporate citizenship? (e.g. involvement with stakeholders, availability of transparent information)

Thank you for filling in the Smart Industry Sustainability Scan. For further questions you can contact us.

7.3 Appendix C: The feedback of experts

Expert 1: consultant on Digital Strategy, Transformation & Innovation, and New Business

In general, the expert thought the aspects were relevant, but he found the measurement questions per aspect too shallow. He proposed to extent the scan by adding more in-depth measurement questions for each aspect. The expert argued that this would contribute to the insight of manufactures about taking the next steps to take following up the scan. In order to do this, the expert proposed to add more questions related to the value chain and footprint, instead of only focusing on the manufacturing process. The expert advised as well to include more information to support the questions, to be as specific as possible. Last, the expert sent me two papers to use to improve the scan.

Part	Feedback	Implemented?
Aspect 1	Add examples of rules and policies to be more clear.	Yes
Aspect 2	Add more in-depth questions about sustainable strategies and how the performance of it can be measured. Also add examples benchmarks, metrices etcetera to be as specific as possible.	Yes
Aspect 3	Also think about transport, energy neutrality.	Yes
Aspect 4	Also think about increasing productivity, modularity, and the sustainability of suppliers, extending product life cycles by means of for example predictive maintenance, service to support customers' sustainability.	Yes
Aspect 5	Also think about the energy use of the whole value chain, and the entire footprint of the organization, add examples of clean water, capturing and reusing heat.	Yes
Aspect 6	Also think about R&D, cooperation partnerships, learning.	Yes
Reading material	Two paper about Sustainable Business Innovation (Young & Gerard, 2021), and Opportunities of Sustainable Manufacturing in Industry 4.0 (Stock & Seliger, 2016).	Yes

Expert 2: a policy scientist and environmentalist, specialized in circular economy, sustainable energy and biobased economy.

General feedback:

The expert provided me with insightful feedback, by helping me to look at the scan from the perspective of manufacturing organizations. In general expert 2 questioned if the specific integration of Industry 4.0 and sustainability is already present for manufacturers, especially for the scope that is assessed in the scan. However, the expert thought the six aspects are covering all important factors, and the sixth aspect about social sustainability is a good aspect to include. Also, the expert thought the scan has a good length. The scan can contribute to raise awareness about how manufactures can be more sustainable, the expert argued. Out of the experts' own experience, many technical organizations are already doing more then they realize. With this the expert means that sustainability is often a by-product of resource- and energy-efficiency, something that manufactures are already trying to optimize for decades. The expert argued that in order for organizations to understand and implement sustainable development, it helps if concepts are recognizable and accessible. Last, the expert mentioned that the SISS would function well as a follow-up of the other scans that IXIA offer. In this way, the general maturity on Industry 4.0 of an organization is assessed first by the SIMS.

Specific feedback:

Part	Feedback	Implemented?
Introduction	- Change the definition of sustainability. The current definition can evoke some negative or biased views. The new definition can be more focused on what manufactures are already doing, and how sustainable development can be improved by Industry 4.0 opportunities.	- Yes - Yes - No, I think it is important to explain the basic idea of Industry 4.0, so that the meaning can be understood. - Yes

	- It can be emphasized more that the scan aims to give organizations more insights in the next steps. - The definition of Industry 4.0 is a bit on the long side. - Add an illustration of all aspects in the introduction, this will give a good overview of what to expect during the scan.	
Aspect 1	For question 1.1 and 1.3 you ask about the awareness of sustainability regulations and policies, whether the degree of compliance to these regulations and policies would be more important to measure. This should be the starting point for every organization on sustainable development.	Yes
Aspect 2	Some questions are overlapping or asking about the same things. This needs to be checked for the other aspects as well.	Yes
Reading material	The expert sent me information that can be found in: "Projectplan CESI-NL Supply, De rol en positie van toeleveranciers in de ontwikkeling van een slimme maakindustrie naar een circulaire economie, Brabantse Ontwikkelingsmaatschappij, maart 2021."	

Expert 3: Engineering doctorate holding professor on Industry 4.0, Factory of the Future and Open Automation

General feedback:

In general, the expert advised to make the scan shorter, so that it would be less time consuming to take. Besides, the experts proposed to translate the scan to Dutch as well. In that case, the term "Industry 4.0" can be replaced by Smart Industry. This term is better recognized and understood by Dutch companies. Further, the expert mentioned that it would be interesting to assess the degree to which organizations realize that sustainability will be an essential aspect of future manufacturing, as well as when that impact is expected to be tangible. The expert explained that the integration of sustainability and Industry 4.0 is not yet realized. Manufactures look at sustainability more as resources issue, and an energy issue that is already seen as solved by the use of for example solar panels. The pricing of CO2 will happen in a few years, which will result in higher cost of materials. Therefore, the expert prefers to look at sustainable development for manufactures from the Recycling-ladder, a model that lays out the different levels of recycling. Expert 3 did not provide further feedback about specific aspects. To conclude, the expert sent me a self-written concept whitepaper about the Dutch Smart Industry.

Specific feedback:

Part	Feedback	Implemented?
General	Make it shorter, so that it is less time consuming.	No, the scan is purposely designed so that it covers the whole range of opportunities Industry 4.0 offers for sustainable manufacturing
General	Assess the degree to which organizations realize that sustainability will be an essential aspect of future manufacturing, as well as when that impact is expected to be tangible.	No, those are more open questions, that will not improve the maturity model.
Aspect 4	Implement the Recycling-ladder.	Yes
Reading material	Self-written concept whitepaper about the Dutch Smart Industry	

Expert 4: former CEO of a company that develops low flow fluidics solutions, and current Strategic Business Developer at the same company, focusing on customer relations, partnerships, digitization and social innovation.

To start, Expert 4 thought the base of the scan was good. For that reason, the expert did not provide feedback on the specific aspects and questions, but rather looked at the scan overall. The most important advice the expert gave me was that given answers on the scan are strongly reliant on the personal interpretation of the person that fills in the scan. The expert noticed that some words can be replaced by other words to fit the context of the sentence better. Besides, there were some mistakes in spelling, or inconsistencies across use of words. Therefore, the expert advised to run an extensive check through the text to make sure it is as clear as possible. Next, the expert pointed out that in the introduction the definitions of the two pillars of the scan, Industry 4.0 and sustainability, are short and simple. This while both concepts are comprehensive and long known. The expert recommended to make the definitions sharper, so that there is less room for personal interpretations of those concepts. The expert also advised to focus more on the "why?" and "what?" in the introduction. Why should someone make the time to do the scan, and what happens with the results. To motivate someone to do the scan, this information should definitely be included the expert explained. Next, the expert advised to give an overview of all the aspects in the introduction, as well as the end. In that way, the person that is doing the scan knows what can be expected. Besides the expert advised to mention why the aspects are chosen. Then, for each aspect the expert pointed out that there is both a general explanation, as well as extra information per question. This repetition suggests that the reader has not understood the general explanation and it makes the document longer than necessary. Therefore, the expert advised to make the general information per aspect short, strong and complete. Then, the questions can be stated without the extra information. Last, the expert gave me some suggestions for reading material about circular innovation and recovery of nature, which are the start and end point of a process. According to the expert, the sustainability concept is more and more moving towards these points and therefore relevant to implement in the scan.

Specific feedback:

Part	Feedback	Implemented?
General	Answers of the scan are reliant of personal interpretations. So be as clear as possible. Some words can be replaced to fit the context better. E.g. semi advanced, Business Models move. Make sure to be consistent, e.g. strategies and performance becomes strategies and measurements later on in the text. Check all text.	- Yes, extra information per question is added in the "i". By adding examples, the question is clarified and room for personal interpretation is smaller. Advanced and semi-advanced are switched, this was a mistake that needed to be corrected. Business model move is changed for sustainable business model innovation. Consistency is checked.
General	- Make the general information per aspect short, strong and complete. Then, the questions can be stated without the extra information. - For abbreviations: first use the full word + abbreviation, from then on only use the abbreviation.	- Yes, the general information per aspects is formulated shorter, stronger and more complete. No, I choose to still add some additional information that can be clicked on for every aspect ("i"). In this way, there is less room for personal interpretation. The general information is provided in the introduction of the aspects, examples are provided in the "i". - Yes
Introduction	- Sharpen the definitions of Industry 4.0 and sustainability, so that there is less room for personal interpretation. - Mention how long it will take to fill in the scan. - Focus more on the why someone should fill in the scan, and what happens with the results. - Make an overview of all aspects in the introductions, as well as in the end. Besides explain shortly why the aspects are chosen.	- Yes, the definition of sustainability is changed to a definition for sustainable manufacturing, which is more focused on the manufacturing industry. No, the definition of Industry 4.0 has remained the same. The application of Industry 4.0 can differ across companies, so the definition needs to be as it is in my perspective. - Yes - Yes

		- Yes, a picture of the aspects is added in the introduction, and in the end the aspects are summarized again. In the introduction is mentioned that the aspects cover the important areas if Industry 4.0 and sustainability. In the introduction of the aspects is shortly mentioned why the aspect is important
Aspect 4	The 3R model is already extended to the 7/8R model.	Yes, the 9R model of (Kirchherr et al., 2017) is selected and implemented.
Reading material	Sustainability is moving towards a focus on the begin and end point of a process: namely circular innovating and recovery. Read about this concept, try to form an opinion, and implement it in the scan.	Circular innovation is already (partly) covered in the question about sustainable business model innovation of aspect 2. A question about ecological restoration is added.

Expert 5: Assistant professor on Environmental and Energy Management, and a European coordinator of Greening of Industry Network. The experts research interests are among others: management of natural resources, product development, circular economy, Corporate Social Responsibility, and social and environmental Life Cycle Assessment

General feedback:

Expert 5 gave me insightful feedback about the contents of the scan. The expert thought de formulation of the questions, and in specific the integration of Industry 4.0 and sustainability, was good. In general, the expert thought the aspects were all important, and the questions clear. For a few aspects and questions the expert made some suggestions.

Specific feedback:

Part	Feedback	Implemented?
Aspect 1	Regulations and policies are crucial to start with. Maybe the sector can be indicated during the scan since different industry sectors have different kind of rules.	Yes
Aspect 2	Not every company can invest in certifications, ISO 14001 is often used by larger companies, small companies often go for the Global reporting initiative. Maybe the size of the company can be indicated at the start.	Yes, asked for at the beginning of the scan
Aspect 3	Also think about the pollution of the air indoors, inside the factory for example.	Yes
Aspect 4	- The second question can be formulated clearer. Make sure that you understand what renewable means, and how Industry 4.0 can contribute to preserve nature. - Water as a resource should be added, how to be efficient with water, and how to ensure water quality	- Yes - No, water falls already under resources
Aspect 6	- Explain that the economic part is already part of Industry 4.0, and this scan focuses on the ecological and social part. - The consumer can be added. Consumer safety for example, but also educating and raising awareness with sustainable campaigns	- Yes - Yes

Expert 6: Program Manager Circular Economy

In general, the expert thought the scan asks the right questions to assess the effect of smart industry on sustainability. The expert is curious to causal relationship between circularity and digitization, as well as what companies expect which smart technologies are needed to become circular. For the quality of the response, the expert mentioned that it is important to look at which person to ask inside an organization. Last, the expert is curious about the practical application of the scan.

Expert 7: Consultant in Information Technology and Services Industry.

In general, the expert suggested to look more at business drivers of an industry. According to the expert, many companies are not focusing on business drivers. In specific smaller members of value chains are missing opportunities because they are not connected to the needs of the manufacturing industry. Besides, the expert mentioned that it would be valuable to assess how a company gains their knowledge, for example through universities, partnerships, or research. This can be easily asked with an open question at the beginning of the scan. Last, the expert noted that for the scan to be understandable, it is important to use a language that is accessible for every reader.

Part	Feedback	Implemented?
General	- Add an open question at the start of the scan, which asks where the company gets their knowledge about Industry 4.0 and sustainability from. - Implement more business drivers into the scan. - Use understandable and accessible language.	- No, this already falls under the questions about cooperation partnerships and research & development. - No - Yes

Expert 8: CEO of a bed manufacturer

The expert thought the scan looks comprehensive and professional. But the expert thinks there lies a challenge in how to make an useful, practical tool out of it. Decision-making regarding strategy and its implementation is often influenced by other factors as well, for example gut feeling and experience. Last, the expert suggests to distinguish the questions more between internal and external factors.

Part	Feedback	Implemented?
General	Distinguish between internal and external factors	No