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Building the maturity model for a sustainable collaborative manufacturing industry

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Abstract: This paper discovers the research path when testing the ManuMaturity model and upgrading it to guide manufacturing companies beyond Industry 4.0, towards data sharing within a supply chain, to an open innovation ecosystem and towards sustainable manufacturing. The original ManuMaturity model has five maturity levels: traditional factory, modern factory, agile factory, agile cognitive factory and agile cognitive industry. Together with the seven dimensions—infrastructure, data, customer, business model, employee and sustainability—it was implemented as an open self-assessment web tool. The tool was tested with a group of manufacturing companies and the feedback was gathered both via the discussions with the manufacturing companies and the service providers. In this paper, the insights are presented as well as the potential additional elements of the extended maturity model.

Keywords: maturity model; open smart manufacturing; open innovation ecosystem; industry X.0; innovation; twin transition; sustainability; data sharing

1. Introduction

Digital transformation provides new business possibilities, but it also creates challenges for manufacturing companies. Aside from manufacturing skills, these companies must also acquire new capabilities. Manufacturing SMEs are struggling with resource constraints and knowledge gaps that slow down their digitalisation efforts and investments. The main challenges and barriers to overcome are limited understanding, insufficient resources and gaps in bringing digitalisation into practice (Heilala et al., 2020; Kääriäinen et al., 2020).

Twin transition and global rising awareness of environmental issues force companies to pursue a circular economy, new R-cycles and even zero defect. Companies have also discovered that collaboration is a new way of working. To enable this, data management rules and platforms for securing private data and sharing data with trusted partners are required. Companies need tools and methods to proceed not only with digitalisation but also towards open innovation, collaboration, data sharing and sustainability goals.

2. Maturity Models

Maturity models (MM) have a long history and many models applied to various topics are published by the academy, alliances and consultancies. For the digital transformation only, dozens of MMs are available that originated from both practitioners and academy (Teichert, 2019). There are also MMs for business processes (Tarhan et al., 2016), information security (Saleh, 2011), responsive research and innovation (Stahl et al., 2017).

The VTT Technical Research Centre of Finland Ltd has developed three maturity self-assessment tools for non-commercial use: DigiMaturity (Leino et al., 2017), AI Maturity (Saari et al., 2019) and ManuMaturity (Saari et al., 2021b). The MMs for sustainability, innovation ecosystems and data sharing are briefly discussed next and various MMs for Industry X.0 in the next chapter.

Sustainability

Sustainability is an emerging topic and the manufacturing industry shall proceed with the twin transition, i.e. enhance their environmental and economic sustainability by implementing new digital solutions and R-cycles, such as refuse, reduce, reuse, repair, refurbish, re-manufacture, re-purpose, recycle materials, recover energy and re-mine (Reike et al., 2018).

One MM for the circular economy proposes maturity levels—such as: linearity, industrial circular economy (CE) piloting, systemic materials management, CE thinking and circularity—and maps them to the manufacturing value chain (Saari et al., 2021a).

Innovation ecosystem

Further, innovation management needs to be considered. Companies are gradually ready to work together when they realise that the challenges of the industry require a wide range of skills and technologies that a small company alone cannot provide. Collaboration and co-creation are easier to start with trusted partners who have already worked with a project, community or ecosystem. There are also MMs for ecosystems, innovation ecosystems (Rozalska-Lilo, 2019) and even innovation ecosystem strategies.

Visscher et. al. introduced four maturity levels: i) the company is not aware of the potential relevance of ecosystems to its innovation process, ii) the company is aware of the relevance of ecosystems to its innovation processes, iii) the company has a coherent innovation ecosystem strategy, iv) the company has coherent and encompassing innovation ecosystem strategy that covers both explorative and exploitative layers (Visscher et al., 2021). For software start-up ecosystems, the maturity levels are as follows: nascent, evolving, mature and self-sustainable (Cukier and Kon, 2018).

Data sharing

The European data strategy aims to make the European Union (EU) a leader in data-driven society. Creating a single market for data will allow it to flow freely within the EU and across sectors for the benefit of businesses, researchers and public administrations (European Union, 2020). The common data sharing space enables data exchange and unlock AI potential. The Big Data Value Association promotes European data sharing space and present the data sharing value wheel with core pillars such as: governance, people, organisations, technology and data (Scerri et al., 2019).

3. Research Method

In this section, we describe our research method, as shown in **Figure 1**. In the development of the ManuMaturity model we follow the MM development approach, which has phases such as i) scope, ii) design, ii) populate, iv) test, v) deploy and vi) maintain (de Bruin et al., 2005). At the beginning of this process more than 50 articles were carefully studied to collect input for the ManuMaturity model. The next section discovers the MMs for the manufacturing industry. Based on the literature, we designed and populated the model. The result, ManuMaturity tool, was implemented as an open self-assessment web tool. The tool was tested with selected manufacturing companies and the findings are presented in Chapter 4.

Figure 1 Research method.

The research question is “How to frame a maturity model that guides manufacturing companies i) beyond Industry 4.0, ii) towards data sharing within a supply chain, iii) to anopen innovation ecosystem and iv) towards a sustainable manufacturing value chain”.

Maturity models for the manufacturing industry

To boost the development and digitalisation of the manufacturing industry, the academy, industrial alliances and consultancies have provided various tools and models. In 2019, researchers reported on 10 academic Industry 4.0 MMs as well as 10 by consultancies (Felch et al., 2019). Several other maturity tools have been developed for Industry 4.0 and the manufacturing industry (Liebrecht et al., 2021; Rauch et al., 2020). The next three tables summarise the MMs having either clear dimensions and maturity levels or other highlighted features, such as recommendations or tools. Table 1 carries academic contributions, Table 2 alliances and Table 3 consultancies.

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Table 1 Academic MMs related to the manufacturing industry or Industry 4.0 (in alphabetic order)

Title and source	*Dimensions*	*Maturity levels*	*Notes on tool or results*
Industry 4.0 technologies: Implementation patterns in manufacturing companies (Frank et al., 2019)	Four digitalisation domains in manufacturing companies: Smart manufacturing, Smart products, Smart working and Smart supply-chain	Adaptation levels of technologies: Low adapters, Moderate adopters and Advanced adopters	
Developing a green supplier maturity model: Concepts, application and limits (Miemczyk et al., 2015)	Organisational structure, Processes, Technology, Control, Collaboration, Human resources, Planning	They list the maturity levels of five separate models, but do not declare their own levels	Focus on green supply.
Assessing the maturity and benefits of a digital extended enterprise. Modelling of a digital extended enterprise (Pulkkinen et al., 2019)	Three key performance areas (KPA) with open questions. Domains are: Strategy, Business model, Processes; Performance indicators, Interfaces and Information flow.	Five maturity levels such as: Non-existent, Individuals, Teams, Company extended enterprise	UI for questionnaire has been implemented and the results can be visualised. The MM comprises of five levels of maturity defined by 69 statements in the KPAs. Four industrial cases are repeated twice.
Industrie 4.0 maturity index - managing the digital transformation of companies (Schuh et al., 2017)	Resources, Information systems, Organisational structure and Culture	Stages in the Industry 4.0 development path: Computerisation, Connectivity, Visibility, Transparency, Predictive capacity and Adaptability	
A maturity model assessing Industry 4.0 readiness and maturity of manufacturing enterprises (Schumacher et al., 2016)	Strategy, Leadership, Customers, Products, Operations, Culture, People, Governance and Technology	Five maturity levels, where the 1st indicates complete lack and the 5th state-of-the-art.	A tool for questions using the Likert scale and a weighting factor was piloted with an Australian manufacturing enterprise. A radar chart for result visualisation.

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Table 2. MMs from alliances related to manufacturing industry or Industry 4.0

Title and source	*Dimensions*	*Maturity Levels*	*Notes on tool or results*
One-stop shop access for European SMEs to ADvanced MAnufacturing support (ADMA, 2019)	Advanced manufacturing technologies, Digital factory, End-to-end customer focused engineering, Eco factory, Human-centred organisation, Smart manufacturing, Value chain-oriented open factory	Five (numeric)	EU project result
The Middle Market Manufacturer's roadmap to industry 4.0 (BDO, 2017)	Six dimensions: Security, Technology, Data, Process, Organisation and Governance.	Five: Stovepipe, Breaking down silos, Integrated Enterprise, Integrated value chain, Adaptable ecosystem	Value chains included
Guideline Industrie 4.0: Guiding principles for the implementation of Industrie 4.0 in small and medium-sized businesses (VDMA, 2018)	Industry 4.0 MM with two main dimensions: product and production	Does not have clear maturity levels but potential implementation pathways for technologies to apply either in products or in production.	Detailed enough to pick the next application or technology for piloting. Aimed for SMEs
Recommendations for the future of manufacturing (WMF, 2018)	No dimensions	No maturity levels	10 recommendations for manufacturing industry. Ideas for the futuristic level (beyond Industry 4.0) nominated as the Agile cognitive industry were partially driven by these recommendations.

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Table 3. MMs from consultancies related to the manufacturing industry or Industry 4.0

Title and source	*Dimensions*	*Maturity levels*	*Notes on tool or results*
The smart factory - Responsive, adaptive, connected manufacturing (Deloitte Consulting, 2017)		5 key characteristics of future factory: Connected, Optimised, Transparent, Proactive and Agile	Unlocking value starts from a single asset and proceeds via production line to factory and factory network.
Vision 2030: The factory of future (Frost & Sullivan, 2017)	8 sectors: Federated manufacturing, Smart innovations, New value networks, Outcome-based services, Connected platforms; Cognitive platforms; Machine dominance; Human capital transformation	No common maturity levels, but unique evolution stages for each sector.	
Industry 4.0: Building the digital enterprise (PwC, 2016)	7 dimensions: Digital business models and customer access, Digitalisation of product and service offerings, Digitalisation and integration of vertical and horizontal value chains, Data and analytics as core capability, Agile IT architecture, Compliance, security, legal and tax and Organisation, employees and digital culture.	4 stages: Digital novice; Vertical integrator; Horizontal collaborator; Digital champion	Tool https://i40-self-assessment.pwc.de/i40/landing/

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As the maturity of the MM research was systematically studied with more than 200 articles, it was found that 46% of the articles focused on model development, 35% presented a model application and 14% focused in model validation. Thus, there seems to be a gap in evaluating and validating the developed MMs (Wendler, 2012). When 15 MMs published towards the Industry 4.0 journey or smart manufacturing were analysed, 3 research gaps were identified: i) differences in the starting conditions between SMEs and Multi-National Enterprises (MNEs) regarding Industry 4.0 or smart manufacturing, ii) disconnection between the MM and the self-assessment tools and iii) support (especially tailored for SMEs) towards proposing the next steps after maturity assessment is missing (Mittal et al., 2018).

ManuMaturity model and tool

In the design phase the architecture of the model that forms the basis for further development is identified. The population phase identified the assessment dimensions and how this assessment can occur in practice, i.e., the instrument (web tool) used in conducting the assessment and the inclusion of appropriate questions and measures (response options) within this instrument (web tool) (Bruin et al. 2005).

The design phase resulted in the ManuMaturity model with seven dimensions in three sectors (**Figure 2**). The (grey) sustainability and employee dimensions contribute to the responsibility sector. Further, the infrastructure and data dimensions together discover the viewpoints of the (blue) technology sector. Finally, the (red) business sector has two dimensions: the business model and the customer. Process dimension crosses all these three sectors and is drawn around the other six dimensions. (Saari et al., 2021b)

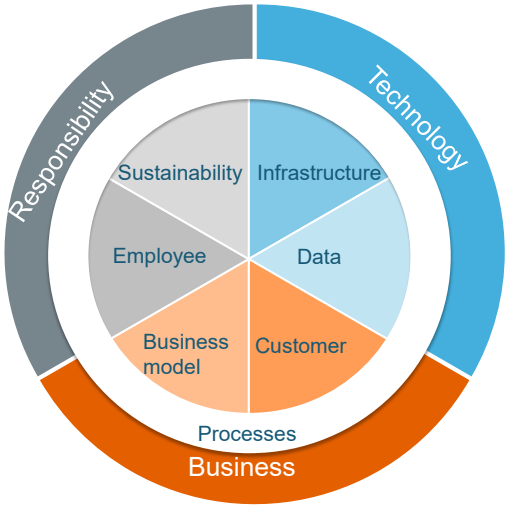

Figure 2 The sectors and dimensions of ManuMaturity.

In the population phase the dimensions were mapped with maturity levels: i) traditional factory with manual data processing, ii) modern factory with dedicated digital processes and islands of automation, iii) agile factory with automated production connected to the production control system, iv) agile cognitive factory with real-time data transmission,

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production control and intelligent automation and v) agile cognitive industry includes intelligent systems and AI powered analytics over the partner network (**Figure 3**).

The ManuMaturity tool was implemented as a self-assessment web tool available to companies for non-commercial use in the beginning of 2020. Each dimension has two to four questions and each question has five prewritten response options reflecting the maturity levels from which to choose. **Table 4** presents the questions for each dimension in the ManuMaturity tool.

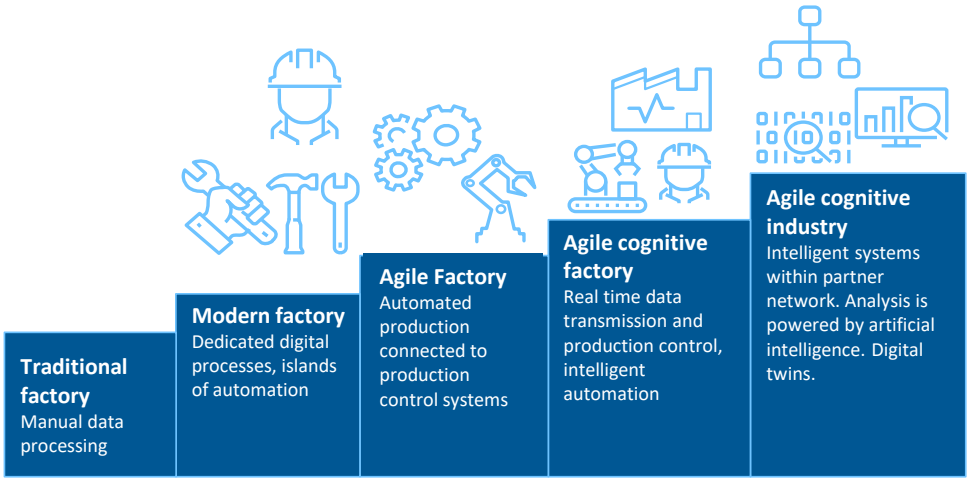

Figure 3 The digitalisation stairs of the manufacturing industry (Heilala et al., 2020).

Table 4 The dimensions and questions of the ManuMaturity tool (Saari et al., 2021b)

Dimension	*Questions*
Customer	How are customer needs and requirements gathered and exploited? How can products be customised?
Business model	What is your company selling? How are innovations mastered?
Processes	What is the status, definition and implementation of processes in your organisation? How is digitalisation exploited in the integration of processes
Data	How is product data collected and shared? How is production process data collected and shared? How is data analysed? How is the exploitability of data ensured
Infrastructure	How are order, product and production data handled? How is agile production enabled? How are systems, networks and programs protected from digital attacks
Employees	How do machines/systems interact with employees? Where is the focus of work?
Sustainability	How are resources used? How are environmental impacts considered?

For the web tool, also the prewritten response options reflecting each maturity level were provided. **Table 5** presents the response options for the innovation process question of the business model dimension (Saari et al., 2021b). **Figure 4** displays an example of the immediate result graph where the responses of the respondent company are drawn together with the average of all other respondents.

Table 5 The response options for "How are innovations mastered?" with responsive maturity level and score.

Maturity level	*Score*	*Response option*
Traditional factory	0	There is no innovation process. Innovations emerge (pop up) ad hoc.
Modern factory	1	Innovations are discovered by a limited group of people. Innovations are sought only against specific challenges.
Agile factory	2	In-house innovation process exists and new ideas are gathered. R&D partner(s) are invited if they have special knowledge or resources.
Agile cognitive factory	3	Customers and supply chain are included in innovation and foresight processes. Agile interaction with R&D partner networks provides the knowledge required to implement innovations.
Agile cognitive industry	4	Partner network co-creates disruptive innovations and shared vision for the future. The network is able to expand beyond its own competences and capabilities.

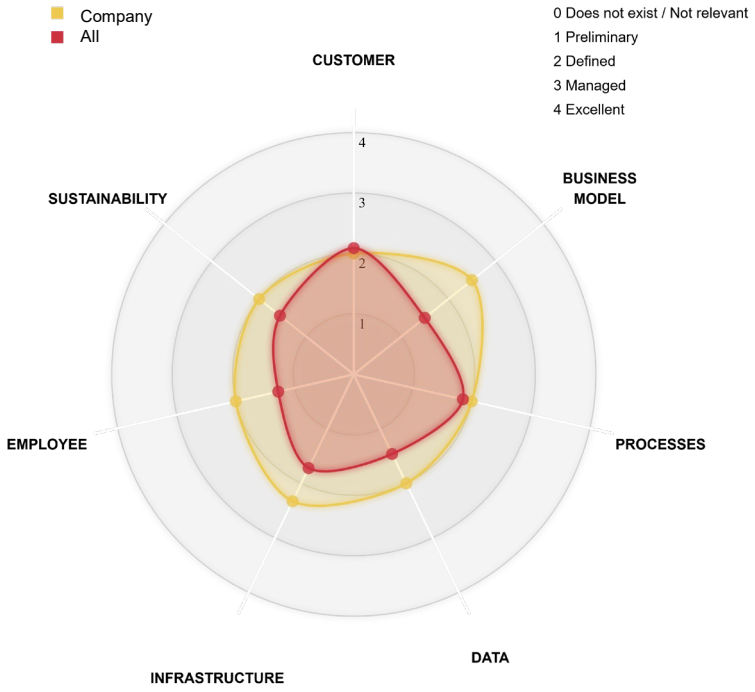

Figure 4 An example of the ManuMaturity result graph.

Testing the ManuMaturity tool

The ManuMaturity tool was tested in February 2022 with the manufacturing companies being partners of the Open Smart Manufacturing Ecosystem (OSME)[1] project. OSME is a collaborative initiative that engages manufacturing companies to speed up the needed transformation by engaging, supporting and leveraging the skills and strengths of its partners.

The pilot companies tested the ManuMaturity model implemented in the web tool. A total of 20 ManuMaturity assessments were received from 8 companies. Three of them represent Multi-National Enterprises (MNE) in the manufacturing domain as the remaining five are SMEs, mainly subcontractors of the MNEs (**Figure 5**). **Table 6** describes those eight companies with the number of responses, size and industrial domain. The companies B, C, D and F belong to the same group of companies and could have been handled here as one respondent having five responses.

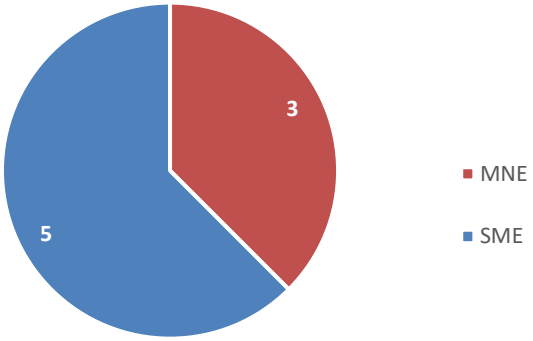

Figure 5 Size distribution of the pilot manufacturing companies.

Table 6 ManuMaturity pilot companies

Company ID	*Number of responses*	*Size*	*Industry domain*
A	2	MNE	27 Manufacture of electrical equipment
B	1	SME	24 Manufacture of basic metals
C	1	SME	33 Repair and installation of machinery and equipment
D	1	SME	24 Manufacture of basic metals
E	1	MNE	28 Manufacture of machinery and equipment
F	10	SME	25 Manufacture of fabricated metal products, except machinery and equipment
G	2	SME	25 Manufacture of fabricated metal products, except machinery and equipment
H	2	MNE	28 Manufacture of machinery and equipment

[1] https://cris.vtt.fi/en/projects/open-smart-manufacturing-ecosystem

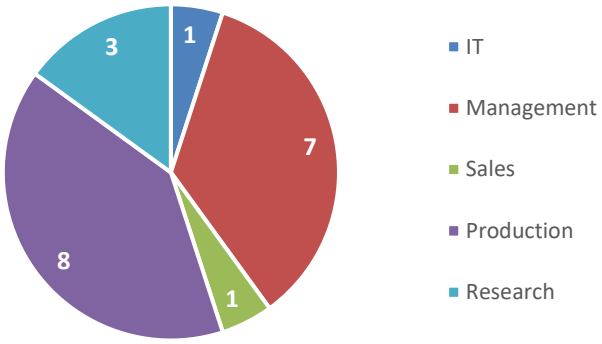

Figure 6 The organisational function of respondents.

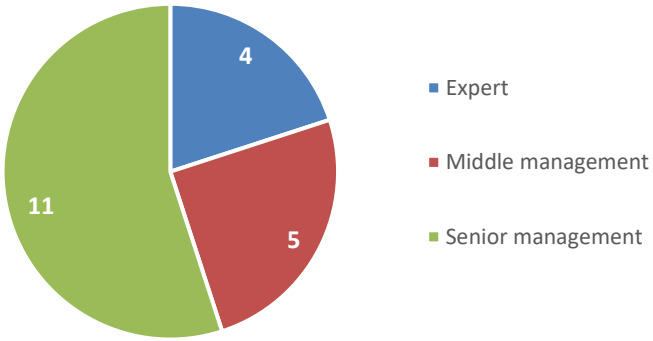

Figure 7 The role of respondents.

Result and feedback sessions

Feedback about the ManuMaturity tool was gathered via discussions with the respondents and the service providers of OSME. The feedback sessions with the respondents were two-part. First, the ManuMaturity results were discussed. The second part collected feedback on the ManuMaturity model, the user experience of the web tool and potential enhancements to the model, tool, or service path. The discussions with service providers were facilitated via the online Miro board. **Table 6** carries the status of feedback sessions. A total of 14 persons from the manufacturing companies provided feedback to the existing ManuMaturity tool and contributed to the extension of MM and tool enhancements.

Table 8 describes the service providers that contributed to the dimensions and questions in the sessions detailed in **Table 9**. A total of four persons contributed to the new MM. The next chapter presents the findings of these feedback sessions.

Table 7 Feedback sessions with the respondents, manufacturing companies

Company	*Senior manager*	*Middle manager*	*Expert*	*Date*
A		1	1	6th April 2022 at 14:30 EEST
B, C, D, G	6			21st April 2022 at 12:30 EEST
E	1		1	11th April 2022 at 11 EEST
G	1	1		25th April 2022 at 10 EEST
H	2			27th April 2022 at 9 EEST
Total	10	2	2	5 sessions

Table 8 The service providers that contributed to the new maturity tool

Company	*Size*	*Industry domain*
I	Medium big	28 Manufacture of machinery and equipment
J	SME	70 Management consultancy activities
K	SME	62 Computer programming, consultancy and related activities

Table 9 Feedback sessions with the service provider companies

Company	*Senior manager*	*Middle manager*	*Expert*	*Date*
I and K	1	1		20th April 2022 at 13:30 EEST
J	1		1	20th April 2022 at 15 EEST
Total	2	1	1	2 sessions

4. Findings

The findings are gathered from the result and feedback sessions with manufacturing companies and discussions with service provider companies. Further, one remarkable MM is highlighted.

Feedback from the ManuMaturity tool

In the feedback discussions several issues arose.

- It is not clear whether a subjective assessment is sufficient. For the holistic assessment of a company several individual responses (with roles from CEO to operator) are required. For example, in MNEs the business model of your department may be different that of others. In addition, you may know that the company has piloted something, but not in your department.

- The questions are clear, even though it is difficult for any individual to cover all dimensions in detail. In some questions the leap between response options (maturity levels) is huge. Case examples were requested. Instead of choosing single option, it should be possible to weight several.
- The maturity levels **(Figure 3)** are not transparent in the tool. Numeric values from 0 to 4 are confusing as numeric values usually start with one.
- The result graph (see **Figure 4**) with dimension score is not self-evident or sufficient. A question-by-question analysis and reflection on response options should be possible in retrospect. Further, the respondents would like to receive proposed next actions, road map and contact points.
- The tool should support the development path of respondent's organisation. It could contain two viewpoints: the assessment of the current status and the future target. The previous assessment (with a time stamp) could be available for comparison. The tool could even point to some sufficient technological implementation cases of peer companies and propose a road map. Another company expressed that they have internal follow-up tools and would not conduct a re-assessment with the ManuMaturity tool.

One MNE provided a single response to the tool, but it was created interactively by a group of three persons with different roles. They were inspired with the tool and its questions as those sparked a lively debate before they chose a mutually agreeable response option. They were also relieved that their results graph showed them to be above the average of all responses. Indeed, such a collaborative response seems to be a good way to engage in internal discussion about the current status of the company.

Contribution to the MM to be renewed

Contribution to the new extended MM was sought from both from manufacturing companies and service providers. The proposals are summarised below:

- Should culture be included? What is the climate of opinion regarding digitalisation among the employees? How are innovations generated or supported?
- Other potential human factors mentioned were work safety, wellbeing, competences and continuous improvement.
- Supply chain data management and data valorisation as new questions to the data dimension.
- Resiliency, foresight and risk management to the business model dimension.

New models

After the ManuMaturity tool, many other models and tools have been published and old ones updated. **Table 9** highlights the Smart Industry Readiness Index (SIRI) claiming to be the world's first independent digital maturity assessment for manufacturers and comprising a suite of frameworks and tools to help start, scale and sustain manufacturing transformation journeys.

Table 10 SIRI

Title and source	*Dimensions*	*Maturity levels*	*Notes on tool or results*
Global Smart Industry Readiness Index Initiative – SIRI (EDB Singapore, 2020; WEF, 2022)	Three building blocks, 8 pillars and 16 dimensions, such as: Vertical integration, Horizontal integration, Integrated product lifecycle, Shop floor automation, Enterprise automation, Facility automation, Shop floor connectivity, Enterprise connectivity, Facility connectivity, Shop floor intelligence, Enterprise intelligence, Facility intelligence, Workforce learning and development, Leadership competency, Inter- and intra-company collaboration, Strategy and governance.	6 stages, 0–5. Each pillar has a different maturity level definition for the stages. For example, maturity levels for process are: Undefined, Defined, Digital, Integrated, Automated and Intelligent.	More than 600 manufacturing companies across more than 30 different countries having completed the Official SIRI Assessment. Link to the SIRI tool

5. Result

The inputs gathered from the testing phase of the ManuMaturity tool, new emerging global trends and published MMs need to be considered carefully. The revised model should remain clear and balanced. The SMEs were disappointed because they considered it unrealistic to reach the highest level. Further, questions related to the business model or products should be tuned or eliminated for subcontractors.

Figure 8 displays the potential new elements (green) of the extended MM. It is possible to introduce new questions without adding new dimensions. The employee dimension title has been expanded to include corporate culture. The new questions will consider both openness to collaboration and attitude towards global challenges The economic pillar of sustainability is placed below the business model dimension while social impact is neglected. Further, discovery is needed on the formulation of response options reflecting the maturity levels in new questions such as resiliency, foresight and risk management. The data dimension will receive new questions related to the data management and sharing in the supply chain as well as data valorisation.

The ecosystemic and collaborative way of working is not proposed as a new dimension because it is already embedded in the highest original maturity level indicating collaboration and transparency within the supply chain or ecosystem (see **Figure 3**). The aim is to reuse the original maturity levels of the ManuMaturity model in the extension.

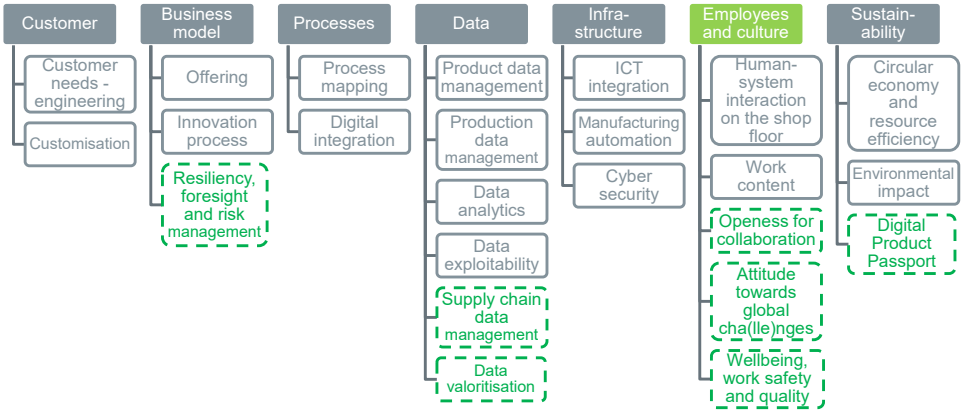

Figure 8 Potential new elements of the extended MM.

6. Conclusions and Further Work

The main result of this research is the new elements proposed for the extended MM based on the ManuMaturity tool tested by both SMEs and MNEs. The goal of the original ManuMaturity model was to guide manufacturing companies towards Industry 4.0 and beyond. Although ManuMaturity already had dimensions for data and sustainability, the feedback from companies and European trends for twin transition and shared federated data pushed towards an extension with additional dimensions or at least questions. The extended MM itself will help companies, practitioners and researchers to understand the current challenges of the manufacturing industry. Further, it will boost co-creation in the open innovation ecosystem by enabling new mutually sustainable processes in the supply chain and even new business opportunities for the service providers.

After final testing, the extended MM will be implemented as an open self-assessment web tool and shared within the manufacturing industry to enable its open exploitation. Further, different usage patterns, such as individual and interactive group assessments will be considered. The authors plan to provide a sufficient service pathway to support the capability building of both manufacturing companies and service providers operating in a supply chain or ecosystem.

Acknowledgements

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