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# Organisational sustainability readiness: A model and assessment tool for manufacturing companies

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ABSTRACT

Manufacturing plays a major role in the economic and social development of society, yet this often comes at a high environmental cost. Despite great advances in our understanding of sustainability issues and solutions developed to tackle this challenge, current production and consumption models are still largely unsustainable. Strong industrial actions are required to move towards safer and cleaner practices respectful of the planetary boundaries. This paper puts forward a novel approach for top and middle management in manufacturing companies to build capabilities for sustainable manufacturing by assessing their organisational sustainability readiness. The proposed model and tool for organisational sustainability readiness were developed based on themes emerging from empirical data collected via interviews and focus groups in six companies. The resulting themes were consolidated and validated with relevant literature to create four levels of readiness, displaying a crescendo of operations management practices on the shop floor that positively affect sustainability performance. Finally, an industrial application was used to further validate the tool and demonstrate how it can help companies develop a roadmap for a more sustainable manufacturing industry.
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## 1. Introduction

Sustainability is a multi-faceted concept, with institutional, economic, social, and environmental dimensions (Elkington, 1997; Spangenberg, 2002). In 2015, the United Nations issued 17 sustainable development goals (United Nations, 2015) which are increasingly integrated in governments' and organisations' agenda. This study addresses the twelfth goal: responsible production and consumption. Production is defined as activities and processes that transform raw materials into products by means of labour, machinery and information (Blanchard, 2004), thus focusing on processes that occur in production facilities and factories, referred to as "production systems" (Bellgran and Säfsten, 2010). Sustainable production can only be achieved when manufacturing processes account for future needs of society and work within the planetary boundaries (Rockström et al., 2009).

Production environments are currently undergoing a transformation induced by the fourth industrial revolution, which adds complexity but also opportunities for sustainable manufacturing. In fact, production systems are transitioning to cyber-physical production systems (CPPS), where the virtual and physical worlds converge (Monostori, 2014) and the value of data is harnessed to achieve desired goals. However, as Tao et al. (2018) pointed out, the lack of convergence between the virtual and the physical worlds leads "to low level of efficiency, intelligence, sustainability in product design, manufacturing, and service phases". Approaches, technologies and methods are therefore needed to reconcile these two worlds and support relevant strategic goals for the manufacturing industry, sustainability included.

For this to happen, "soft aspects" at a company or corporate scale come into play when change is introduced in a system, such as competences and capabilities. In the 1990s, management scholars Teece and Pisano (2003) noted the time dimension of competences and capabilities, as they highlighted the importance of management capability to effectively adapt to changing environments by "re-configuring internal and external organisational skills and resources". These components of responsiveness and adaptation are core parts of the sustainability management field. For example, Dangelico et al. (2017) built a framework for green product

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innovation in the manufacturing industry by using sustainability-oriented dynamic capabilities as theoretical foundations, highlighting the value of a capability-based approach in the pursuit of sustainability-oriented changes.

With this background, this study aims to support manufacturing companies in assessing their readiness relating to a desired capability for sustainability. This is in line with helping manufacturing companies' management tackle the goal of sustainable production (Barletta, 2019). Fig. 1 clarifies the relationship between the various terms and concepts forming the conceptual framework of this research. The term "readiness" was preferred to address manufacturers' needs for building sustainable manufacturing capabilities, rather than the maturity level of a specific capability. As a result, an organisation scoring high in sustainability readiness suggests that the corporate sustainability strategy is being implemented, i.e., strategy and operations are aligned. This nuanced concept is called organisational sustainability readiness (OSR).

The research question (RQ) is: What are the key factors that contribute to a manufacturing company's organisational sustainability readiness? To answer the RQ, an OSR model for the manufacturing industry was proposed. A tool was developed to make use of the model with two design requirements: (1) standalone usability in industry, requiring no mediating role between the user and the tool, and (2) scalability so the tool can be adapted to remain applicable to any discrete manufacturing company, irrespective of size, secondary sector, location, and technology intensity. Regarding the scope of the study, the research adopts a resource-based view of the firm on management practices and decisions on organisational design (Wernerfelt, 1984; Kraaijenbrink et al., 2010), while excluding external factors such as stakeholder engagement (Lozano et al., 2015) and HR issues.

The remainder of the paper is structured as follows: Section 2 reviews the literature on relevant topics. Section 3 presents the methods employed for the model development and tool testing. Section 4 presents the results to answer the RQ. Section 5 discusses the implications of the findings and limitations of the study. Section 6 summarises and concludes the paper with a summary of the contributions to knowledge and industry.

## 2. Literature review

In this section, relevant topics for the tool development are explored through a literature review: subsection 2.1 focuses on organisational capabilities for sustainable manufacturing and subsection 2.2 focuses on maturity models to evaluate those capabilities.

### 2.1. Sustainable manufacturing capability

Inspired by the four principles of The Natural Step Framework (Robèrt et al., 1997; The Natural Step, 2018), sustainable manufacturing can be defined as the set of transformation processes and supporting business processes that creates products in a way that: (1) enables nature's functions and diversity to flourish, minimising the concentrations of substances produced by society, and conserving resources in the Earth's crust; (2) guarantees long-term profitability of the supply chains realising the product; and (3) contributes positively to the physical, psychological, and social wellbeing of employees, product users and affected local communities—extended version of the definition by the US Department of Commerce (International Trade Administration, 2007).

Accordingly, sustainable manufacturing strategy is defined as "a business strategy that embeds the above principles of sustainable manufacturing." However, in a corporate context, a sustainable manufacturing strategy can be defined as any strategy that realises the manufacturing company's sustainability goals. Hayes and Pisano discussed two foundational concepts for "beyond world-class manufacturing": organisational capabilities and learning organisations (Hayes and Pisano, 1994). They note that consistent performance improvement does not necessarily come from the adoption of specific improvement programs, but from management's effort in identifying and building manufacturing capabilities that are relevant for the company's competitiveness; e.g. a capability for a manufacturing line would be "process flexibility" as the ability to change between products quickly (Rousseva, 2009; Swink and Harvey, 1998; Upton, 1995).

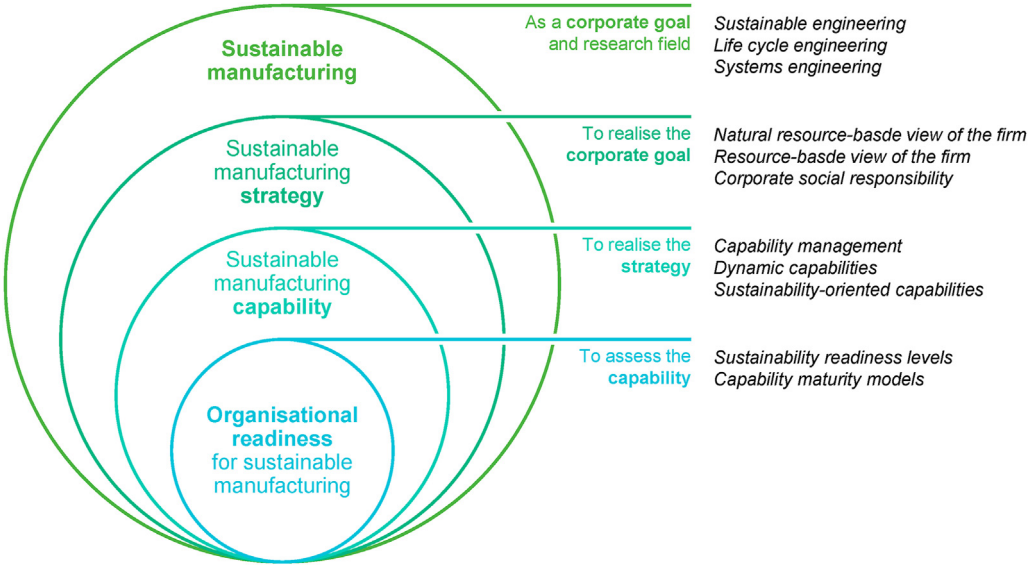


**Fig. 1.** Conceptual framework showing key terms used in this research, including a short definition and a visual representation of their relationships.

Based on Hayes and Pisano's argument, corporate sustainability performance of manufacturers is likely to improve systematically if sustainable manufacturing capabilities are identified, built and nurtured (Hayes and Pisano, 1994). In this paper, the concept of sustainability-oriented dynamic capabilities (Teece and Pisano, 2003; Demirel and Kesidou, 2019) is foundational in the conceptual framework shown in Fig. 1. Dynamic capabilities allow management to reconfigure skills and resources in response to a changing environment (Teece and Pisano, 2003). Sustainability-oriented dynamic capabilities are defined as an "ability to integrate, build and reconfigure competences and resources to embed environmental sustainability into new product development to respond to changes in the market" (Dangelico et al., 2017).

In this paper, a *sustainable manufacturing capability* is a sustainability-related capability that realises the company's sustainable manufacturing strategy in two specific corporate areas: product development (Neely et al., 1995) and operations management (Kleindorfer et al., 2005). For instance, "product stewardships" and "pollution prevention" (Amini and Bienstock, 2014) are sustainable manufacturing capabilities derived from a natural resource-based view of the firm (Hart and Dowell, 2011).

### 2.2. Organisational capability maturity models

Organisational maturity is tied to capability management. The concept of organisational maturity is based on a view of the organisation as a learning and evolving entity. Each evolutionary stage builds on the previous ones and is characterised by a maturity level. When the characterisation model targets capability and performance, then the model used is a capability maturity model (CMM). The maturity levels encompass situations where the capability is non-existent, being built, developed, and optimised (Porter and Tanner, 2012). The first CMM was created to evaluate software subcontractors in the military industry (Paulk et al., 1993; Paulk, 2002). A process-level improvement program called "capability maturity model integration" (CMMI Institute, 2019) was later developed to address best practices in three areas: (1) product and service development, (2) service establishment, management, and (3) product and service acquisition. When performance benchmarking is used, companies that use CMMs are able to learn about the effectiveness of continuous improvement plans (Reis et al., 2017).

The number of maturity models in the engineering field has grown dramatically since the 1990s, as evidenced by a review of 52 models by von Wangenheim et al. (2010) and another review of 237 articles on maturity models by Wendler (2012). The latter claimed that theoretical-reflective publications evaluating and validating maturity models are scarce. With this knowledge gap in mind, this paper focuses on implementing a specific type of CMM and assessing its usefulness. Therefore, the review of capability maturity models performed in early stages of this research aimed to identify a potential candidate to use as a baseline model relevant to the purpose of this research rather than create a new model. The articles reviewed focused on organisational learning and performance management with respect to corporate sustainability. The articles were mapped using two dimensions and listed in chronological order in Table 1. The first dimension is the scope of the model which indicates whether the model is applicable in the manufacturing-oriented domain or in a cross-industrial domain. The second dimension is the category of the model based on an existing classification (Wendler, 2012):

- *concept/construction*: conceptual or design-oriented maturity model,
- *description*: existing maturity model applied for presentation purposes,
- *mapping/comparison*: existent maturity models are compared to each other or discussed in relation to specific concepts,
- *assessment*: the maturity of industries and organisations are assessed (not to be confused with validations of maturity models),
- *transfer*: an existing maturity model is applied to another domain,
- *empirical study*: maturity models are developed, applied or validated through quantitative, qualitative or mixed-method empirical studies,
- *theoretical reflection*: theoretical implications of maturity models are discussed.

The content analysis revealed that ten papers reported practical examples to demonstrate the use of the proposed models: Ngai et al. (2013); Pigosso et al. (2013); Vimal and Vinodh (2013); Golinska and Kuebler (2014); Introna et al., (2014); Dubey et al. (2015); Thomas et al. (2015); Jovanović and Filipović (2016); Meza-Ruiz et al. (2017); and Sangwan et al. (2018). These studies used pilot testing based on qualitative and mixed methods, except for Dubey et al. (2015), which used quantitative verification and validation.

The "sustainable manufacturing maturity model" (SMMM) proposed by Mani et al. (2010) was selected as a baseline model to build on, because of two reasons: 1) its characteristics match those of objectives and RQ of the current study, and 2) the high-level structure of the model as per illustrated in Mani et al. (2010) had not been further developed in subsequent studies. Mani et al. (2010) outlined motivation and needed efforts for the development of a comprehensive yet user-friendly capability maturity model for sustainable manufacturing. The SMMM, when fully implemented, would focus on production systems and manufacturing processes as object of analysis. However, Mani et al. call for product-oriented life-cycle management tools to be embedded in the use of the model as well. Such a design, combined with best practices of clean production, performance indicators and standards for manufacturing process characterisation render the model holistic in an extent and scope that are aligned to those of this study.

Other models included in the review also showed good potential: the ecodesign maturity model by Pigosso et al. (2013) for product-design applications, and the sustainable operations maturity model by Machado et al. (2013).

## 3. Methods

This section presents the research process followed in this study. Subsection 3.1 provides an overview of the research methods used and the timeline of activities for the model development and tool testing. Subsection 3.2 describes the model development process based on both prior work found in the literature and new empirical data collected from companies. Finally, subsection 3.3 describes the tool used to test the model and the method for calculating the maturity score.

### 3.1. Research design

This research used case studies and an abductive approach. Case studies were used as building blocks for theory generation, as defined by (Yin, 2013) and discussed by Eisenhardt (1989) and Eisenhardt and Graebner (2007). The model development was an abductive process, alternating inductive and deductive reasoning

**Table 1**
Mapping of maturity models proposed in the literature for sustainable manufacturing capabilities.

| | Scope | |
|---|---|---|
| Category | Manufacturing-oriented domain | Cross-industrial domain |
| Concept | Mani et al. (2010)<br>Machado et al. (2013)<br>Ngai et al. (2013)<br>Vimal and Vinodh (2013)<br>Jain and Rachuri (2014)<br>Roberts and Ball (2014)<br>Romero and Molina (2014)<br>Dubey et al. (2015)<br>Thomas et al. (2015)<br>Sangwan et al. (2018) | Cagnin et al. (2005)<br>Silvius and Schipper (2010)<br>Edgeman and Eskildsen (2014)<br>Introna et al. (2014) |
| Empirical | Pigosso et al. (2011)<br>Pigosso et al. (2013)<br>Golinska and Kuebler (2014)<br>Machado et al. (2017) | Domingues et al. (2016) |
| Mapping/Comparison | Cherrafi et al. (2016) | Siew et al. (2016) |
| Transfer | Pigosso and McAloone (2016) | Jovanović and Filipović (2016) |
| Description | Verrier et al. (2016) | NA |
| Assessment | N/A | Meza-Ruiz et al. (2017) |

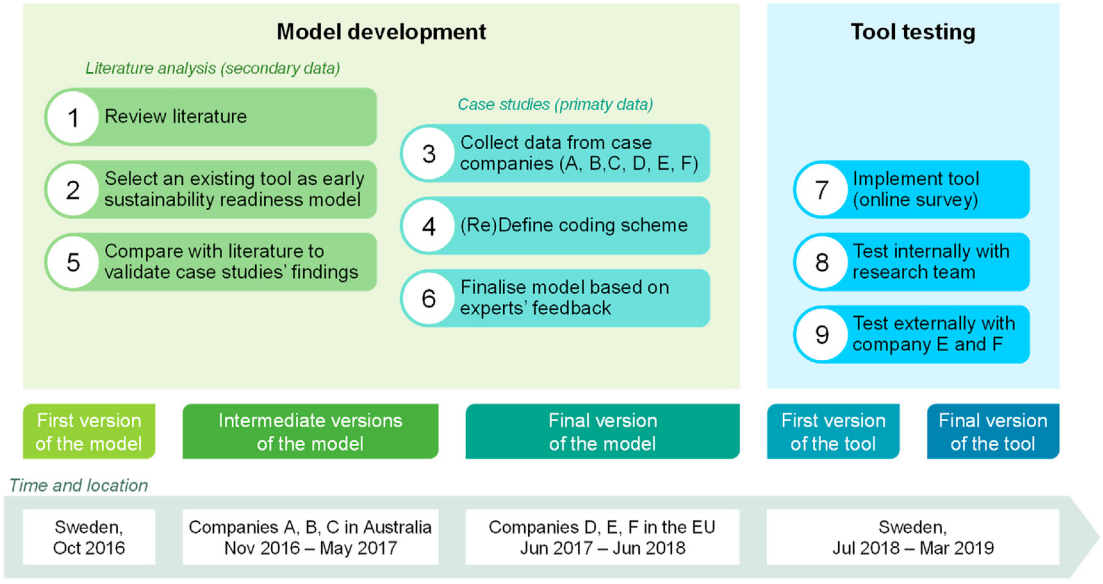


**Fig. 2.** Timeline of the research activities for model development and tool testing.

(Dubois and Gadde, 2002; Timmermans and Tavory, 2012) to create a model from combining theory, empirical phenomena and case study methodology (Dubois and Gibbert, 2010).

The research was performed with a series of activities organised in two stages: model development and tool testing. Fig. 2 shows the timeline of the research activities. Activity 1 and 2 focused on the literature review and the selection of a baseline model. After empirical data collection (activity 3), an interplay between theory and empirical data occurred (iteration of activity 4 and activity 5) to produce the final OSR model (activity 6) as explained in subsection 3.2. In the final step (activities 7, 8 and 9), the model was converted into a tool for practical use, and then it was tested and validated as explained subsection 3.3.

### 3.2. Model development

#### 3.2.1. Selection of a baseline model from the literature

Potential candidates to be used as a baseline model were identified in the literature. The literature search was performed on Scopus and Google Scholar databases, limited to articles published in English between 2005 and 2019; and narrowed down to subject areas of "Engineering", "Environmental Science", "Decision Science", "Business, Management and Accounting" and "Social Sciences" (in Scopus only). To secure high quality standards, selected journals and conference proceedings were prioritised. Book chapters were evaluated case by case.

The literature search was performed produced a sample of 44 publications. Seven additional publications were added based on peer recommendations and snowballing method, resulting in a total of 51 publications. The capability maturity models presented in these publications were evaluated. The relevance of the models was assessed using the following relevance criteria: (1) focus on capability management; (2) target the manufacturing industry; (3) relate to corporate sustainability. A total of 25 publications passed the relevance test and were included in the literature review of this paper. The results of this literature review are reported in subsection 2.2.

Although the baseline model was selected in October 2016, the literature review was regularly updated to draw insights from these

new models and validate the findings from the company cases. Thus, the review of maturity models includes newer models published between 2016 and 2019.

### 3.2.2. Data collection from case companies

Data were collected over 12 sessions (eight interviews and four focus groups) involving 17 participants across the six company cases from different industry sectors. Table 2 shows the companies involved in developing the model, the number and role of participants, and the data collection methods. Observation of Companies A, B, C, and F took place during study visits, either at the factory or shipyard. Notes and pictures were taken to document processes and work in progress. Secondary data from the company's website, white papers and press releases were used when relevant. In Companies C, D, E and F, data were gathered from focus groups. If gathering multiple participants in one session was not possible, then individual in-depth interviews were carried out.

Two rounds of model development occurred: one in Australia (Companies A, B and C), and one in Europe (Companies D, E and F). In the first round, the SMMM was used as a mediating object for interviewing. Codes were generated inductively (Miles et al., 1994) and grouped in categories. The initial data collection used ten interview questions focused on identifying the core capabilities connected to the company's sustainable manufacturing strategy. The questions enabled participants to connect the concepts of business strategy and core capabilities with corporate sustainability. A summary of key discussion points was sent to the participants for feedback to check the accuracy of the data collected.

In the second round, codes obtained in the first round were used deductively. Statements from the interviews and focus groups in Companies D, E and F were coded, placed in the model architecture to test the emerging themes empirically. Note that Company E and Company F are industrial project partners in the EU-project "ECO-PRODIGI" (Centrum Balticum Foundation, 2019) sponsored by the Baltic Sea Region. This project aims to innovate the value chain of the maritime industry through digital solutions (Lasi et al., 2014) for eco-efficiency (DeSimone and Popoff, 2000); e.g., project activities included the use of 3D scanning and virtual reality used to create digital twins (Tao et al., 2018) of vessels and critical components, and advanced simulation to reduce fuel consumption in ship operations.

### 3.2.3. Data analysis

Empirical data from the case companies were analysed through qualitative coding to group the data (statements from interviews/focus groups) into categories and themes, as well as readiness levels. Hence, the OSR model resulted in a 2D matrix, as illustrated in Fig. 3.

The first dimension is composed of "systems" that need to be managed by manufacturers to improve economic and environmental sustainability performance. For each system, themes were included in the model if they met two conditions: 1) the theme is in the scope of the study, and 2) the theme fits within established corporate sustainability theories. The themes were included in the model by converting them into statements. For example, the theme "data accuracy" is broken down into several statements, each representing a level of accuracy of data, and finally into questions for the OSR tool (e.g., "how accurate is the data?").

The second dimension is composed of the increasing organisational readiness levels. Hence, the textual characterisation (statements) of each cell represents the extent to which a certain management practice/decision improves economic and environmental sustainability performance. To assess the OSR level, the tool user evaluates what statement fits their company's situation best.

The themes and levels descriptions were checked against the scientific literature on sustainability management and sustainable manufacturing. This allowed to consolidate the wording and ensure construct validity (Yin 2013).

## 3.3. Tool testing

The practical contribution of this research was achieved through the conversion of the OSR model into a tool in the form of a 10-min questionnaire. The tool is generic by design and was tested internally to ensure the terminology was unambiguous. A few iterations were necessary to find a balance between ease of use and complexity without compromising the value of the results. The tool was tested with manufacturing companies to validate the themes

**Table 2**
Description of the companies involved in the case studies and data collection methods.

| | Company A | Company B | Company C | Company D | Company E | Company F |
|---|---|---|---|---|---|---|
| Sector | Optics | Confectionery | Materials Handling | Maritime | Maritime | Maritime |
| Country | Australia | Australia | Australia | Sweden | Lithuania | Finland |
| Number of employees | 35 | 50 (excl. parent company) | 500 | 100 | 400 (incl. parent company) | 1400 |
| Product family | Glasses and frames | Moulding equipment | Heavy trucks | Vessel (any type) | Vessel (any type) | Cruise vessel |
| Operations analysed | Components production, final assembly | Final assembly, refurbishment | Final assembly | Ship reparation, final assembly | Ship reparation, final assembly | Shipbuilding |
| Number of participants | 1 | 3 | 5 | 2 | 2 | 4 |
| Company role of the participants | R&D and operations manager (cross-functional role) | General manager<br>Marketing manager Pacific Area<br>Production manager | CEO<br>Production manager<br>Engineering design manager<br>Accounting manager<br>HR manager | Vice director of production<br>HSEQ manager | 3D scanning technology practitioner<br>Director of maintenance | Head of R&D sustainability manager<br>UX sustainability designer<br>PLM implementation lead |
| Methods (instances) | Observations at the production facility (1), in-depth interviews (2) | In-depth interviews (3), observations at the production facility (1) | Focus group (1), in-depth interview (1), observations at the production facility (1) | Focus group (1) | Focus group (1) | Observations at the shipyard (1), focus group (1), in-depth interviews (2) |

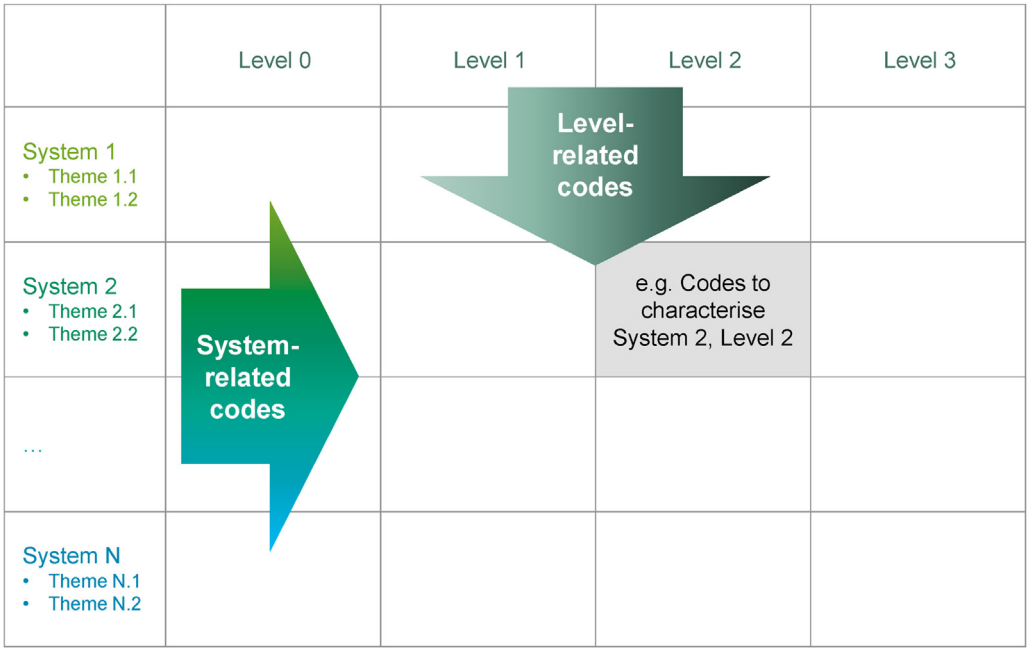


**Fig. 3.** Approach adopted for clustering and merging codes extracted from textual data to develop the organisational sustainability readiness model.

in the OSR model and assess the tool usefulness. The software provider was Qualtrics (2019). A non-anonymous survey link was distributed to the industrial partners in the ECOPRODIGI project (case companies E and F). Respondents' feedback was collected during and, when possible, also after the tool testing. In fact, the survey contained five follow-up questions to evaluate user experience, and follow-up emails were sent to those respondents willing to engage in an in-depth discussion.

The survey started with an introduction to the purpose of the tool and introduces the terminology used. The respondent is then asked to focus on a specific capability to be evaluated. Some examples are provided as prompts to ensure "capability" is understood as intended (e.g. "pollution prevention", "zero-waste production"). Then the capability was evaluated through series of questions and multiple-choice answers focusing on the six socio-technical systems in the OSR model. The lists of questions and answers are provided in Appendix B.

The score produced by the survey was named organisational sustainability readiness score and annotated *OSR*. It is the average ($\mu_i$) of the readiness levels of each of the *N* "systems to manage" represented by $i = 1, \ldots, N$. The *OSR* is defined in equation (1):

$$OSR = \frac{\sum_{i=1}^{N} \mu_i}{N} \tag{1}$$

A meaningful variable to consider when evaluating the survey's results is the standard deviation across the N "systems to manage", represented by $OSR_\sigma$ for and defined in equation (2).

$$OSR_\sigma = \sqrt{\frac{\sum_{i=1}^{N} (n_i - 1)\sigma_i^2}{\sum_{i=1}^{N} (n_i - 1)}} \tag{2}$$

In equation (2), each $\sigma_i^2$ are the sample variances of the scores assigned to each system *i*, composed of $n_i$ questions. Equation (3) defines the individual $\sigma_i^2$.

$$\sigma_i^2 = \frac{1}{n_i - 1} \sum_{j=1}^{n_i} (y_{ji} - \mu_i)^2 \tag{3}$$

In equation (2), $y_{ji}$ corresponds to the readiness level that the tool user assigned for each in the *j*-question regarding the *i* system, with a minimum value of 0 and a maximum value of 3. Since the survey developed had two questions for each system *i*, equation (3) is simplified as per equation (4):

$$\sigma_i^2 = (y_1 - \mu_i)^2 + (y_2 - \mu_i)^2 \tag{4}$$

The calculations above do not apply any weight to the individual OSR sub-scores for each socio-technical system, but this could be added if the user deems certain systems to have a higher priority over others. The current tool does not prescribe such prioritisation and therefore no weighting factors were applied.

## 4. Results

This section presents the main results from the study as follows: subsection 4.1 describes the empirical data collected from multiple company cases in the manufacturing industry. The findings from the empirical data analysis brought the model to its final version as presented in subsection 4.2. Subsection 4.3 goes on to provide an account of how the model was converted into a tool which was tested in an industrial application. Finally, additional noteworthy results emerging from the model development and tool testing are presented in subsection 4.4, some of which are further discussed in section 5.

### 4.1. Sustainable manufacturing capabilities at the case companies

The "sustainable manufacturing maturity model" (SMMM) developed by Mani et al. (2010) was selected as a baseline model to build on, because its characteristics match those of objectives and RQ of the current study. The study participants, top and middle management in the company cases A, B and C, were asked to use

the SMMM, describing how well it applies to their case. If the SMMM did not apply, the study participants shared what was needed in the company to build sustainable manufacturing capabilities. Interestingly, the discussions focused on the "satellite" systems (beyond production systems) to support sustainability management in production.

The study participants answered the question "What are the sustainable manufacturing capabilities of your company?" with prompts to provide examples; e.g. "zero-waste production", "pollution prevention" and "design for disassembly and remanufacturing". Table 3 lists the capabilities surveyed from the company cases (reworded using the authors' own terminology for consistency across cases). The SMMM (Mani et al., 2010) focuses on manufacturing process performance in terms of process stability (van Schalkwyk, 1998) and process characterisation (Mani et al., 2014) using the same levels of the CMMI (CMMI Institute, 2019): level 1 – Initial, level 2 – Managed, level 3 – Defined, level 4 – Quantitatively Managed and level 5 – Optimised. Mani et al. stated that "the challenge is to identify levels of maturity with well-defined indicators and metrics." The SMMM describes increasing levels of process performance control in sustainability initiatives, projects and practices at the production system level. The conceptual version of the SMMM includes nuances of employees' effort in joining/delivering for sustainability-related projects and building best practices for sustainability. Process performance measurement and control is facilitated through the adoption of tools from life cycle management, such as life cycle costing (LCC), environmental product declaration (EDP), and quantitative techniques of data analysis This was discussed with Companies A, B and C with respect to the prospect of a practical use.

Four lessons learnt from the company cases resulted in specific design choices of the OSR model as presented in the next section. First, the SMMM better applies to capabilities which require performance stability and which were particularly production-oriented (ID15 in Table 3) as opposed to product-oriented (ID3). Second, it was unclear whether the SMMM encompassed sustainability-oriented practices only, programs only or initiatives only, or combinations of these elements. Each of these can be evaluated using different logics and expectations. As a consequence of this "blended approach", the SMMM combined different types of management-related themes within the same level. This might cause uncertainty in the attribution of the right maturity level. Third, it was difficult for some of the study participants to find instances of management practices that belonged either to level 3 (Defined) or level 4 (Quantitatively Managed). Hence, the distinction between these levels was sometimes considered blurry. And fourth, the OSR model applies to one sustainable manufacturing capability at a time to ensure focused answers. Results that reflect the overall organisational readiness are obtained by merging the results from each individual assessment.

### 4.2. Organisational sustainability readiness model

In the data synthesis process, the corpus of empirical data gathered from the company cases was organised in two dimensions: themes (grouped into categories and later converted into "systems to manage") and levels of readiness. This section presents the findings from the company cases which resulted into the final version the OSR model.

#### 4.2.1. Categories and themes

Themes and categories emerged from the analysis the interviews and focus groups in all company cases. A description of the categories with related codes and excerpts are provided in Appendix A. Table 4 presents the main categories and related themes. It is worthwhile to remind that here a "theme" is a description of a set of decisions or actions that it is believed by the study participants to affect the production system's economic and environmental performance positively. Each of theme was checked against the scientific literature on sustainability management and sustainable manufacturing.

The category *manufacturing processes* was included in the final model as a direct consequence of the choice of the SMMM as the "baseline model". In fact, the SMMM mainly includes themes related to process performance monitoring and control.

The category *physical-technical systems* was included after a modification as it covered two different systems: one pertaining to fixed assets, and the other pertaining to materials and consumables used on the shop floor; therefore renamed "assets" and "materials" in the model. The theme of quality and efficiency of materials was integrated with the previous two as it was considered as highly valid and relevant. There is extensive research on material flows modelling for material efficiency and consequent environmental performance improvement (Abdul Rashid et al., 2008; Allwood et al., 2012; Schmidt and Nakajima, 2013; Smith and Ball, 2012). The importance of production assets' maintenance management for sustainable manufacturing was illustrated in (Garetti and Taisch, 2012; Liyanage, 2007).

**Table 3**
List of sustainable manufacturing capabilities shared in the interviews and focus groups.

| Company | ID | Sustainable manufacturing capability |
|---|---|---|
| A | 1 | Producing a durable yet flexible frame (eyeglass = product) |
| | 2 | Closing the material loop in the product's bill of material |
| | 3 | Product modularity |
| B | 4 | Product modularity (mogul machine = product) |
| | 5 | Refurbishment of old moguls |
| | 6 | Easy product maintenance by customer |
| C | 7 | Product modularity and customisation (heavy truck = product) |
| | 8 | Continuous improvement of internal efficiency and production quality performance |
| | 9 | Mobile software (e.g., apps) to track customers' effective use and maintenance practices |
| | 10 | Keeping up with new technology at a factory level |
| D | 11 | Punctuality of ship-repair operations |
| | 12 | High-quality standards of ship reparations |
| E | 13 | Resource efficiency at the shipyard |
| | 14 | Product quality (precision of components' size) (spare parts for vessels = product) |
| | 15 | Efficient and effective retrofitting |
| F | 16 | Resource efficiency at the shipyard |
| | 17 | Zero waste production and keeping resources and values in the loop |
| | 18 | Information transparency of the bill of materials (BOM) across the product's life cycle (product = cruise ship) |

**Table 4**
Categories and themes for organisational sustainability readiness emerging from empirical data.

| Category | Themes |
|---|---|
| Manufacturing processes | Capturing and unifying the knowledge of transformation processes.<br>Monitoring and controlling product and production performance. |
| Physical-technical systems | Securing quality of materials and consumables.<br>Securing efficiency in the use of materials and consumables.<br>Securing quality and efficiency performance of production equipment. |
| Data and information | Collecting, storing, managing and using an "appropriate" data infrastructure (software applications). |
| Information and communication technologies (ICT) and analytic tools | Enabling quantitative, statistical analysis for/in product life cycle management and production system's management. |
| Governance | Adopting a leadership style suitable to organisational culture and organisations' needs.<br>Incentivising employees.<br>Defining clear roles and responsibilities of employees. |
| Competences | Capturing, storing and maintaining relevant knowledge in a shared platform affect the production system's economic and environmental performance positively.<br>Developing relevant organisational competences.<br>Note: knowledge is here "relevant" if it contributes to build which the sustainable manufacturing capability. |

The two categories *data and information* and *ICT and analytic tools* were also included after modification. These two categories were re-arranged to avoid redundancies across themes and renamed "information systems" and "data-driven decision support". Zhang et al. (2017) make the case for building an information architecture based on big data analytics for product lifecycle by reviewing existing literature on cleaner production and by empirical demonstration. The authors listed several barriers hindering cleaner production and product life cycle management processes that are ascribable to availability and accessibility of information related to produced products and supply chains.

All the themes within the category *governance* were excluded. Ogbonna and Harris (2000) argues that "leadership style is not directly linked to performance but is merely indirectly associated", i.e. organisational culture "mediates" the association between leadership style and performance. In addition, the complex nature of corporate incentives to promote desired behaviours (Frey and Osterloh, 2001) makes it difficult to include statements in an evolutionary model. Epstein et al. (2010) stated that "organisational design, performance evaluation, and incentive systems that motivate employee behaviour … alone haven't typically been successful in implementing corporate sustainability strategies".

Finally, the category *competences* was included in the model as capability maturity models are grounded on the concepts of organisational learning. Furthermore, Robinson et al. (2006) and Smith and Sharicz (2011) highlight the centrality of knowledge creation and knowledge management to achieve corporate sustainability goals. Thus the category of competence development encompassed the theme of knowledge management.

As a consequence, the updated model included six new categories corresponding to the socio-technical systems (described in Table 5) inside a manufacturing organisation which help build sustainable manufacturing capabilities: 1) manufacturing processes, 2) assets, 3) materials, 4) data-driven decision support, 5) information systems and 6) organisational competences. These are called "systems to manage" in the OSR model to avoid confusion with the original categories.

#### 4.2.2. Readiness levels

The strength of link between each system's management approach and the achieved "maturity" of the sustainable manufacturing capability in the organisation is modelled through four increasing readiness level (as opposed to maturity) of an organisation, from level 0 to 3. Related codes and excerpts for each level are provided in Appendix A.

The score values are defined as follows:

**Score 0 – unprepared.** The organisation is not ready to build the sustainable manufacturing capability across its management systems (manufacturing processes, assets, materials, data-driven decision support, information systems, and organisational competences).
**Score 1 – novice.** The organisation is learning to build the sustainable manufacturing capability across its management systems.
**Score 2 – almost ready but static.** The organisation has built the sustainable manufacturing capability across its systems, but does not secure continuous improvement of the performance connected to the capability.
**Score 3 – ready, continuous improver.** The organisation built the sustainable manufacturing capability across its systems and strives for continuous improvement of the performance connected to the capability.

### 4.3. Industrial application via a survey tool

The OSR model was converted into a tool to enable its use by manufacturing companies. The OSR model was made useable via a 10-min questionnaire. A non-anonymous survey link was distributed to the industrial partners in the ECOPRODIGI project (Company E and Company F). The beginning of the survey aimed to profile the respondent, acting as a gatekeeper. In the case of company E, the respondents were identified as externally-contracted consultants for the company being evaluated, thus did not qualify to undertake the self-assessment. Distributing the survey to more suitable respondents from Company E proved to be a challenge, especially because of time-constraints issues and privacy issues.

The response rate was 30% with 20 individuals in Company F, operating in the shipbuilding industry. Across the whole set of respondents, the capabilities for sustainable manufacturing that were inserted by the respondents in the test phase were: "pollution prevention", "fuel alternatives for cruise ships", "zero-waste production in a circular economy", and "rapid and virtual prototyping". These are, according to the ECOPRODIGI project partners, the capabilities to build for an eco-efficient supply chain in the shipbuilding industry.

When the model is used in practice, each of these systems have its own individual system readiness score with respect to a specific capability. This "partial" score is indicated with $\mu_i$, with standard deviation of $\sigma_i$ ($i = 1 \ldots 6$ as shown in Table 6). The model includes two statement-like, multiple-choice questions per system, that capture the main aspects of the systems to manage as described in Table 5. Hence, the OSR model is composed of 12 statements to be evaluated by the respondent.

**Table 5**
Description of the systems to manage for sustainable manufacturing capability building.

| System to manage | Description |
|---|---|
| Manufacturing processes | The knowledge of and management of manufacturing processes. In line with Total Quality Management, the focus is placed on the stability of those processes (i.e., the process performs as expected), and use of sustainability-related standards. |
| Asset | Management of fixed assets (machinery, computers, robots, physical infrastructure) that enable and support the processes above. Aspects in focus are assets' availability and quality (compliance to specifications). |
| Materials | Management of consumable materials (e.g., water, lubricants, machining tools, packaging materials) that enable manufacturing processes to work as expected. Aspects in focus are efficiency in material use and quality of materials. |
| Information systems | Management of company's information and communication technologies (ICT). Examples of ICT systems in manufacturing are apps, software, computer programs and data-driven decision-making tools for material resource planning (MRP) and enterprise resource planning (ERP). Aspects in focus are data availability and data accuracy for the data used by ICT systems, as opposed to architectural aspects of ICT systems. |
| Data-driven decision support to management | Management's use of the system of resources that provide data for sustainable decision making in product and production development. The focus is on the use of data-driven decision-making tools and the approach with which quantitative KPIs are used. Examples of data-driven decision-making tools relevant for sustainable manufacturing are cost-benefit analyses, environmental footprint analyses, modelling and simulation tools applied to production systems. |
| Organisational competences | The knowledge held by the organisation through its employees and the existing knowledge management. Examples of components that are part of knowledge management systems are document management systems and communities of practice. The focus is on the approach with which organisational competences are developed. |

**Table 6**
Variables used in the scoring system of the OSR tool.

| System to manage ($i$) | | Mean of readiness ($\mu_i$) | Standard deviation of readiness ($\sigma_i$) |
|---|---|---|---|
| 1 | manufacturing processes | $\mu_1$ | $\sigma_1$ |
| 2 | assets | $\mu_2$ | $\sigma_2$ |
| 3 | materials | $\mu_3$ | $\sigma_3$ |
| 4 | data-driven decision support | $\mu_4$ | $\sigma_4$ |
| 5 | information systems | $\mu_5$ | $\sigma_5$ |
| 6 | organisational competences | $\mu_6$ | $\sigma_6$ |

For each question, the respondent has five choices available and is compelled to pick one option only: each of the four (out of five) options links to a readiness level (from 0 to 3), whereas the fifth option allows the respondent to select the non-applicability of the statement. The full set of questions and answer options per system are placed in Table B1, Table B2, Table B3, Table B4, TableB5, and Table B6 in Appendix B.

It appeared that the respondents did not have a unified view of the sustainable manufacturing capabilities of Company F, although "pollution prevention" and "zero-waste production in a circular economy" may partly overlap. The low response rate and the variability of the main input data (the capability) to the questionnaire suggested that composing an aggregate OSR score and $OSR_\sigma$ for Company F was not practical at the testing stage.

However, it was interesting to observe the perceived readiness level that the respondents had for each individual system. Even with the inability to draw summarising conclusion, observing partial data would still give valuable information about sustainability readiness. Surprisingly, manufacturing process management had a lower sustainability readiness ($\mu_1 = 1.5$ and $\sigma_1 = 1.2$) compared to the score for information systems ($\mu_5 = 1.75$ and $\sigma_5 = 0.94$). These results probably derive from a sampling issue connected with the nature of the ECOPRODIGI project, which focus on digital technologies for the maritime industry. Such a focus may have caused the invited respondents to overfocus on ICT-related issues in production. The importance of such technology-related capabilities is expected to increase as a consequence of advances in digital technologies brought by the fourth industrial revolution (Monostori, 2014; Devezas and Sarygulov, 2017).

At the end of the survey, the respondent automatically obtains the OSR score, the standard deviation $OSR_\sigma$, the individual readiness scores per system to manage $\mu_i$ ($i = 1 \ldots 6$), alongside its standard deviation $\sigma_i$. The respondent also received a report as a downloadable file.

The overall response, summarised in the OSR score, shows how well, on average, the six systems support the sustainable manufacturing capability. Hence, the OSR score indicates how well the corporate sustainability strategy of a manufacturing company is supported in practice. Fig. 4 shows the OSR model and the OSR score as the average of the six sub-scores per system.

### 4.4. Summary of lessons learnt from the model development and tool testing

Subsection 4.1 illustrates the progressive collection of empirical data from the company cases followed by the analysis and interpretation of this data to answer the question: "What are the key factors that contribute to a manufacturing company's organisational sustainability readiness?" The steps presented in subsections 4.2 and 4.3 culminated in the OSR model and tool. Some noteworthy results emerged from the model development and tool testing in the form of two salient lessons learnt shared here for the benefit of model/method developers in the space of capability maturity and corporate sustainability in manufacturing.

Firstly, five out of the six "systems to manage", which constitute the pillars of the OSR model, turned out to be parallel systems that complement and support the primary manufacturing processes, rather than being simply subordinate to them. As such, the OSR model and the resulting tool answered the research question in multiple ways. This discovery demanded a re-thinking of the necessary stakeholders in manufacturing companies to be considered when a model of this kind is being developed. Relevant questions that model developers should ask during various model-development stages are: "Which stakeholders would be the most suitable to approach in order to collect the necessary data for a fit-for-purpose sustainability readiness/maturity model?" and "What are the critical information flows within the company that highlight the interplay between the systems within the model's scope?"

**Fig. 4.** Example of organisational sustainability readiness score.

Based on the answers to such questions, researchers can allocate the role of "project sponsor" to those best fitted from within the company. This would undoubtedly maximise the value of the tool for the target industry or sector.

Secondly, a series of "beta tests" of the survey tool were undertaken by "beta respondents"; i.e., respondents across academia and the industry whose responses were not formally included in the study. These tests generated feedback to improve the OSR tool. In particular, the most valuable piece of information pertained to the balance between the likelihood of a high response rate (decreasing as the number of survey questions increase) and comprehensiveness of the tool (increasing as the number of survey questions increase). The OSR tool as presented in this manuscript includes two questions per "system to manage". However, the consideration of strategies to increase tool comprehensiveness without reducing the response rate should be considered in the future. Such a balance might come with a tool focused on a specific manufacturing sector, for instance. With such a focus, the tool's user would recognise the questions being asked as highly pertinent to the improvement needs they wish to articulate and pursue.

## 5. Discussion

In this section, the authors discuss the implications of the results presented in this paper. Subsection 5.1 presents the authors' reflections on the findings within the context of part and current research efforts. The novelty and limitations of the work presented is then discussed in subsection 5.2. Both subsections highlight the need for further effort to create a tangible impact on manufacturing practices towards sustainability.

### *5.1. Reflections on the findings in the context of prior work*

This research focused on sustainable manufacturing capabilities. The proposed OSR model and associated tool aims to help companies assess their organisational readiness relating to specific capabilities to achieve sustainable manufacturing. The sustainable manufacturing capabilities shared by the case companies as well as the associated themes emerging from the empirical data analysis were already well-addressed in the literature published a decade ago (e.g., DeSimone and Popoff, 2000; Liyanage, 2007; Epstein et al., 2010; Hart and Dowell, 2011). Although the findings of this study did not uncover new capabilities or new themes, they are well-aligned with the literature, thus demonstrating good construct validity of the OSR model.

Continuous updates to the literature review revealed interesting studies performed concurrently to this research, some of which could be included in the maturity model evaluation (e.g. Meza-Ruiz et al., 2017; Machado et al., 2017; Sangwan et al., 2018) and others published later (e.g. Demirel and Kesidou, 2019; Benedetti et al., 2019). However, the baseline model by Mani et al. (2010) was retained as the baseline due to its high suitability to the study aim. Only minor modifications to the categories were needed to reflect the socio-technical systems to be managed in manufacturing companies. This new categorisation allowed the themes to be grouped in a more meaningful manner for industrial applications of the tool. This novel structure of the OSR model along with the themes represent the main contribution of this study. Since the model includes themes for "information systems" and "data-driven decision making", it is highly relevant for organisations aiming to increase the digitalisation of their manufacturing operations.

Finally, another broader reflection on the findings of this study is the fact that sustainability principles are still scarcely put into industrial practice. Sustainability principles themselves have not undergone major changes since the late 1990s, and this research confirms the theoretical findings from prior work in the area of sustainable manufacturing. This is a clear call for better supporting tools to accelerate the transition towards sustainable manufacturing and sustainability in general.

### 5.2. Novelty and limitations of the OSR model and tool

The OSR tool differs from other capability maturity assessment in the way that the users input their data. The organisational sustainability readiness model focuses on "sustainable manufacturing capabilities" without prescribing a specific set of capabilities. Therefore, the users have the freedom to select the one(s) they deem as most critical to achieve a positive trend in sustainability performance. This allows the tool to be more inclusive and adapt to an individual company's sustainability strategy. However, this feature may create unpredictability of the model's fitness for certain sets of capabilities which were not considered or surveyed by the authors beforehand. Even so, the model may be used to evaluate a set of capabilities which are widely recognised as critical for long-term sustainability in the manufacturing industry.

The approach adopted for the model development constitutes a factor of novelty: the OSR model was developed by eliciting and analysing empirical data (primary data) and also reviewing the literature (secondary data). All of the previous models found in the literature review used only secondary data. Wendler (2012) called for evaluation and validation of maturity models, as those proposed in the literature are often untested.

The usefulness of the OSR tool was evaluated based on survey respondents' feedback. Five out of six respondents answered that they "somewhat agreed" with the statement "these results suggest the priorities to tackle by management for increased sustainability performance". Four out of six respondents answered "somewhat agreed" with respect to the statement "these results suggest a course of action for increased sustainability performance". Those who did not find the results helpful selected the motivation that "the answers to the questions did not describe the situation of my company". One possible explanation for this result is that manufacturing companies moving towards product servitisation found the part of the model difficult to apply.

Most notably, the tool testing carried out with a shipbuilding company concluded that the tool is able to indirectly prescribe a course of action for getting production systems "more ready" for sustainable development. However, these results cannot be generalised to the whole Company F. Furthermore, the number of participants involved in the testing phase was limited by data-protection issues under the European regulatory framework and could not trespass the boundaries of the ECOPRODIGI project. Therefore, an abductive and case-study research was performed to partially mitigate this issue, comparing the OSR model with the literature.

A relevant question related to the completeness of the model is: to which extent does the readiness score translate into an actual alignment between sustainability strategy and operations in production systems? Organisational behaviour (e.g., corporate culture, leadership style) has a significant role in effective strategic alignment. Aspects of governance emerged during the interviews and were consequently included in an intermediate version of the model. Unfortunately, there was insufficient empirical data and literature data to substantiate all the four readiness levels on governance affecting sustainability performance. Further research is needed to explore this area empirically.

Finally, the tool was generic by design as it targets the manufacturing industry broadly. The main drawback of this design decision is that the OSR tool does not make specific recommendations. Instead, it informs the user about the strengths and weaknesses of their current capabilities by pointing to broad an "improvement area" or "solution space" for socio-technical systems with a low score on specific OSR themes (rather than directly suggesting improvements or solutions). This relates to another area of concern regarding the usefulness of the overall OSR score. The aggregation mechanism to calculate the final OSR score aims to provide an index for the capability assessed and can be used as an indicator to support continuous improvement of this capability. However, the value of the tool lies in the sub-scores for the individual socio-technical systems and OSR themes. Therefore, the practical contribution of this study relies heavily on the expertise of the tool users. This could be partially addressed by suggesting concrete solutions or examples of best practices on the back-end of the OSR assessment results, but such recommendations would most likely require industry-specific versions of the tool.

## 6. Conclusion

The main contribution of this study is twofold. First, an organisational sustainability readiness model was developed based on primary and secondary data, including empirical data from interviews and focus groups with 17 individuals from 6 companies. Second, the organisational sustainability readiness model was converted into a web-based tool for practical use, called the organisational sustainability readiness tool. This model evaluates capabilities representing manufacturers' potential in realising their desired sustainability strategy. Target users are decision-makers with top and middle management positions. The results from testing the tool are further discussed to draw recommendations for future model development and implementation in industrial practice. The evidence collected in the testing phase showed that the tool helps motivate and support decision-making for sustainability improvements. Given the production-oriented nature of the tool, improvement areas may be found e.g. in new manufacturing technologies and training programs to encourage "green" behaviours on the shop floor. Finally, the tool can be integrated in toolboxes used by companies for internal benchmarking and roadmapping for sustainability.

## CRediT authorship contribution statement

**Ilaria Barletta:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Mélanie Despeisse:** Methodology, Validation, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **Steven Hoffenson:** Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Björn Johansson:** Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125404.

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