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Review

The concept of sustainable manufacturing and its definitions: A content-analysis based literature review

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ABSTRACT

The concept of sustainable manufacturing (SM) is becoming increasingly mature due to the focus on many of its research topics for a long time. This research has undoubtedly extended the body of knowledge, yet the numerous definitions of SM in prior art still indicate a lack of consensus on the true meaning of the concept. It is thus to be expected that these discrepancies will constrain further development and use of the SM concept in industrial practice.

The goal of this paper is to analyze the different definitions of SM and identify the current understanding of what researchers mean by the concept. We use an inductive content analysis of definitions published from 1990 to 2016 in a variety of academic journals. A total of 189 articles including a manifest definition of SM and 89 original definitions were identified. Our analysis revealed that the most commonly used definition is the one proposed by U.S. Department of Commerce in 2008; 63% of the analyzed articles cite or slightly rephrase this definition, while 86% of the identified definitions are used in less than three articles. Although the majority of researchers seems to agree upon eleven sub-categories of SM, a wide range of issues (67 sub-categories) associated with SM indicates inconsistency in the general understanding of the concept. It is proposed that the findings in this study can serve as a foundation for the development of a common language for SM in both research field and industrial practice.

Contents

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1. Introduction

After several decades of research in SM, there is still no common definition among scholars. Moreover, many authors argue that there is no common and unified understanding of what SM is (Dornfeld, 2009), (Haapala et al., 2013), (Wang et al., 2016), (Millar and Russell, 2011), (Despeisse, 2013), (Nakano, 2009), who all highlight the problem of numerous definitions (Jawahir and Bradley, 2016). state that "there are no generally accepted or universal definitions for sustainable manufacturing … there are many insufficient attempts". The definitions evolve as authors modify definitions or interpretations of SM. This situation makes it difficult for industry to take the concept from theory to implementation.

One of the reasons behind the large number of definitions is the many different interpretations of the 'sustainability' concept: e.g., seeing sustainability as an environmental initiative; as a goal or a process; as an integration of different aspects; or as a compromise between pillars, etc. Researchers claim that the large number of terms and definitions in the SM research field is a barrier to sharing knowledge, particularly between academia and industry. This calls for a more common terminology and vocabulary to enable effective communication in the field of SM (Despeisse et al., 2012). Differences between the terms used to define SM can lead to misinterpretations of its true meaning and thus how to implement the concept in the industry. This prevents organizations from forming a clear picture of SM, which is needed to implement associated practices. This is supported by the empirical study conducted by (Ihlen and Roper, 2014), who concluded that corporations make no attempt to explicitly define the sustainability concept, thus pursuing sustainability with unclear strategies. While some organizations make efforts to implement SM practices, the lack of a standard terminology constrain dissemination of best practices among manufacturers (Despeisse et al., 2012) (Garretson et al., 2016). argue that a common terminology is essential for development and implementation of best (SM) practices in the industry.

The objective of this work is to identify and analyze the definitions of SM in prior art, as well as to identify the current understanding of what researchers mean by the concept using an inductive content analysis. In other words, the study aims to determine any variability in the understanding of SM as a concept and its content.

The remainder of this paper is structured as follows. Section 2 presents the methodology used in this study. Content analysis as a method to analyze definitions is introduced and its three main phases, preparation, organization and reporting are described. Section 3 discusses the findings from the content analysis. Finally, concluding remarks are drawn in Section 4.

2. Research methodology

Content analysis has previously been used in social science to analyze definitions; e.g., "social participation" (Levasseur et al., 2010), "green supply chain management" and "sustainable supply chain management" (Ahi and Searcy, 2013), and "corporate social responsibility" (Dahlsrud, 2008). Content analysis is currently an established method that also may be used to gain insight into the SM field. Inductive content analysis has been used previously to advance the understanding of the sustainable agriculture concept by (Velten et al., 2015), who conducted a structured literature review of papers that engaged critically with the definitions of sustainable agriculture and applied content analysis to identify categories associated with sustainable agriculture concept.

2.1. Content analysis as a research method

Content analysis is a type of qualitative study, which is defined as "a research method for the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes and patterns" (Hsieh and Shannon, 2005). Further, it is a systematic reading for making replicable and valid interferences from texts or other symbolic matter (Krippendorff, 2012). The purpose of using content analysis as a research method is to provide new insights and increase the understanding of a specific phenomenon, and to gain a broader and more condensed description of the phenomenon, as well as to describe and quantify a phenomenon.

Content analysis as a method includes both quantitative and qualitative research strategies. Quantitative analysis gives the result in the form of frequency, typically answering the question 'how many'. Qualitative analysis presents data in the form of categories, enabling interpretation of the text (Bengtsson, 2016).

Two approaches to content analysis can be distinguished: inductive (conventional) and deductive analysis (Moretti et al., 2011). The choice of the approach is determined by the main purpose of the study. Deductive content analysis is recommended when the purpose of the study is to test a theory. Inductive content analysis is used when there are no previous studies that deal with the phenomenon or when the former knowledge is fragmented. The advantage of inductive content analysis is that information is gained directly from the data without imposing preconceived theoretical perspectives.

When performing a content analysis, a decision should be made whether a latent or manifest content will be analyzed. A manifest content is the obvious components—what the text says—while the interpretation of the underlying meaning of the text is a latent content (Graneheim and Lundman, 2004).

One of the challenges of content analysis is the lack of a common recipe or standard for execution of it. Therefore, the quality of content analysis has been discussed widely by researchers; see, e.g., (Koch and Harrington, 1998). In the case of content analysis, terms such as validity, reliability, and trustworthiness have been used to address quality of the study (Elo et al., 2014). Trustworthiness becomes particularly important for inductive content analysis since the categories are created from raw data without a theory-based categorization matrix. Therefore, in order to improve the scientific value of our research to be presented herein, the following three phases of inductive content analysis will be described in detail below: preparation, organization and reporting.

2.2. Preparation phase

Preparation phase consists of a collection of the suitable data and making sense of the data (Elo et al., 2014).

2.2.1. Unit of the analysis

The preparation phase starts with the selection of the unit of the analysis (Guthrie et al., 2004). Since the purpose of the research is to identify the current understanding of the SM concept, we chose a manifest definition of 'sustainable manufacturing' as a unit of the analysis.

2.2.2. Data collection method

To identify definitions used by researchers, the search of articles that include definitions of SM was chosen as data collection method.

2.2.3. Sampling strategy

Articles that include a definition of SM—either cited (secondary) or original—have been the object of the search. The following databases were used: ScienceDirect (www.sciencedirect.com), Scopus (www.scopus.com), and the Google Scholar database. In total, 1587 articles in ScienceDirect, 4832 in Scopus, and 14,500 in Google Scholar include the term 'sustainable manufacturing' from January 1990 up until December 2016.

To limit the number of papers for review and to identify the most relevant articles, the following search criteria were applied:

- The following search words were used: ("sustainable manufacturing is") OR ("sustainable manufacturing is defined") OR ("define sustainable manufacturing"), OR ("sustainable manufacturing" AND ("is defined" OR "define" OR "definition")) utilizing "All fields" category.
- The data range was chosen for the entire period, including the year 2016, which means that papers published in 2017 have been excluded.
- When a reference was made to a definition published earlier, the original source were retrieved for further review, whenever available.
- Only articles written in English were considered.

The use of our search strategy could possibly result in the exclusion of relevant articles. For example (Miller et al., 2010), use terms as "green, or sustainable, manufacturing is defined …". In addition, articles could potentially be excluded if a definition is given without the use of the word 'definition'; for example, "sustainable manufacturing can be understood as". Moreover, terms as "sustainability in manufacturing", "manufacturing sustainability", "sustainable production", "green manufacturing", and "industrial ecology" have not been considered in our search—even though some researchers tend to use these terms as synonyms for "sustainable manufacturing".

Although the literature search was extensive, it should not be confused with a state-of-the-art review. However, we claim that the sample size is sufficient to provide a basis for the different interpretations of SM made by researchers over the past 26 years. Fig. 1 shows the number of papers that include the term 'sustainable manufacturing' in ScienceDirect and Scopus databases from 1990 through 2016, representing the sample of papers chosen for further analysis.

Since most of the papers are published after 2008, all articles that include the term 'sustainable manufacturing' in "All fields" (abstract, title, keywords, etc.) from 1990 through 2008 have been reviewed (343 in Scopus and 119 in ScienceDirect). In addition, a search was conducted in the Journal of Cleaner Production in ScienceDirect database with search words 'sustainable manufacturing' AND 'definition' in "All fields", published from 1990 through 2016. Altogether 108 articles were found and reviewed, and among these only eleven articles include a clear definition of SM.

The identified papers were analyzed in detail to ensure that they include an explicit definition of SM. Articles containing the term without a definition were excluded from the further analysis. Some papers include the term 'sustainable manufacturing' but fail to define the concept; for example, in the paper (Brundage et al., 2016), the authors refer to SM in context of performance indicators, yet without defining the term.

2.3. Organization phase

As the result of the search process, 189 articles were selected for further reading and analysis. Each of the papers was carefully reviewed to identify an explicit definition of SM. Each definition was read carefully to ensure correct interpretation before further analysis.

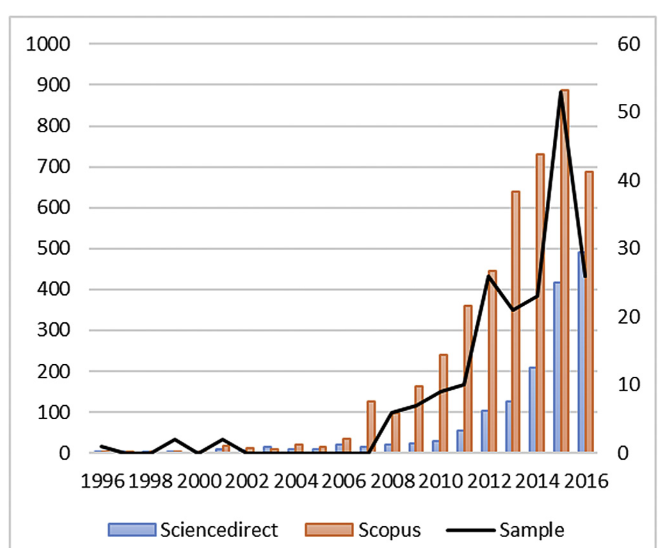

Fig. 1. Distribution of papers using the term 'sustainable manufacturing' chosen for analysis.

All definitions were coded using NVivo 11 software. The coding categories were derived directly from the terms. The use of preconceived categories was avoided to allow the categories and their designations to be extracted from the raw data. This strategy enabled new insights to emerge during the course of the study.

After the categories were defined, both qualitative and quantitative analyses were accomplished. The goal of the qualitative analysis was to present data in words and categories, facilitating interpretations of the analyzed text. The quantitative analysis aimed to present facts from the text in the form of frequency as a number of articles by category, a number of original definitions of SM, a number of the most commonly used definitions, and a number of the most used terms and concepts. The quantitative analysis also enabled analyzing the definitions in chronological terms and to see how the understanding evolved over time.

2.4. Reporting phase

The common critic of content analysis is that journal articles usually focus on the reporting of results, rather than describing the analysis process (Elo et al., 2014). To increase the research significance of this study, the analysis process is presented in the result section, including the choices made during the analysis.

3. Results and discussion

The goal of the current analysis is to identify categories providing representations of how researchers define SM, and the underlying ideas and conceptions associated with this concept. Altogether 189 papers have been carefully reviewed and the different definitions have been analyzed using inductive content analysis. When a paper included more than one definition, all its definitions were coded. First, the definitions from all articles were extracted and interpreted in order to obtain a sense of the whole. Then, the definitions were interpreted carefully to derive appropriate coding. In the first round, the code labels emerged from the text. In the second round, codes were reviewed and renamed, if appropriate. Then, the codes were sorted into 10 categories and 78 sub-categories. Appendix A presents the categories, sub-categories, a number of articles that include codes from the sub-category, along with examples of text coded into each sub-category.

The sub-categories have been analyzed chronologically, and the frequency of sub-categories for each year is presented in Appendix B. The variety of sub-categories was continuously increasing from 2008, with the exception of 2011. Only ten sub-categories appear after 2011. This may indicate some evolvement in the understanding of SM as a concept. Moreover, the majority of articles published after 2008 defines SM according to the U.S. Department of Commerce, as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound”. This particular definition was cited or rephrased in 120 articles (see Fig. 2, definition [10]).

Eighty-nine original definitions have been identified during the review of selected articles. Fig. 2 shows the reference number of the paper with the definition presented in brackets (see Appendix C for the complete list of identified articles and definitions), as well as the number of articles that use the same definition outside the circle. It should also be noted that some articles include more than one definition. Here nine definitions were identified to appear twice while 68 definitions were used only once.

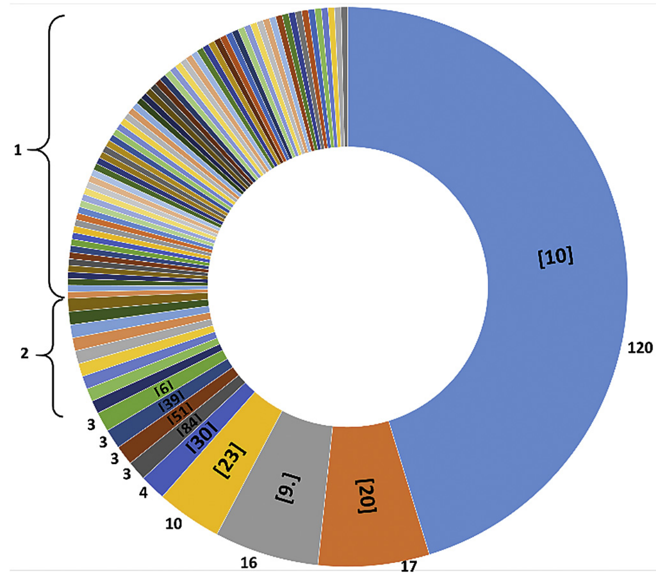

Fig. 2. Frequency of original definitions use.

3.1. Terms defining the ‘sustainable manufacturing’ concept

A review of the different definitions reveals inconsistency as to how ‘sustainable manufacturing’ is referred to in the literature. For example, some authors define SM as a strategy or approach, whereas others define it as paradigm or system. Fig. 3 shows terms that various authors use to define SM. Most of the articles (126) define SM as a ‘creation’ or ‘production’ of product and services. The majority of these papers use the definition proposed by U.S. Department of Commerce. Here the terms that appear only in one article are grouped in sub-category ‘Other’; examples are given as “an effort”, “the science and technology”, “the set of systems and activities”, “a vision”, “the essence of business”, “the global closed-loop supply”, “management”, “the technique, policies and the procedures”, “application of practices”.

The diversity of terms used to define SM is an indication of the lack of agreement among scholars about the true meaning of the concept. The interpretations spans from seeing SM as a strategy to a production system or a global closed-loop supply system.

3.2. Life cycle perspective

The life cycle perspective is commonly associated with the SM concept. End of life management, so-called ‘Re’ strategies and life cycle assessment (LCA) have been widely researched—and in

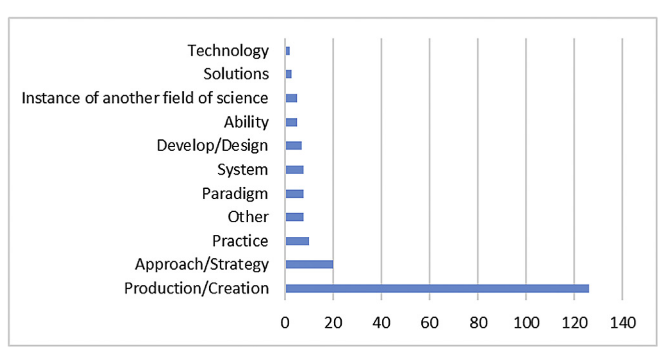

Fig. 3. Terms defining ‘sustainable manufacturing’ concept.

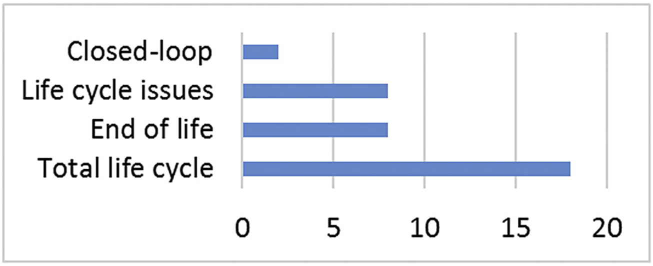

Fig. 4. Number of articles that include 'life cycle perspective' in a definition of sustainable manufacturing.

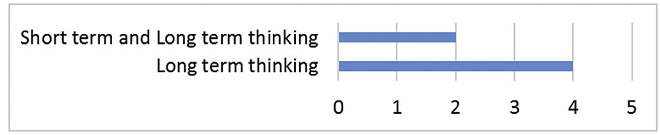

Fig. 5. Number of articles that include 'time perspective' in a definition of sustainable manufacturing.

many cases implemented in companies. Despite the popularity of the life cycle perspective, our analysis shows that researchers rarely include this into the definition of SM. This is illustrated in Fig. 4, which shows that eighteen articles mention total life cycle of products or services, while eight articles refer to life cycle issues.

Closed-loop production systems and closed-loop supply chains can be achieved using different approaches such as 'Re' and DfX (Design for excellence or X) strategies. These can contribute to both the reduction of negative environmental impact and increase of economic benefits (Winkler, 2011). states that closed-loop production systems improve sustainability and lead to improvements in economic and environmental performance of an organization. However, we found only eight articles in this review to include end-of-life issues such as recycling, reuse, remanufacturing, etc. Also, only two articles use a closed-loop aspect in connection with the definitions; closed loop product life cycle (Lee et al., 2014) and closed loop supply chain (Abullah et al., 2015).

3.3. Time perspective

Sustainable development is recognized by international organizations and national governments as a long-term oriented strategy (Kemp and Martens, 2007). Sustainable development concerns both current and future generations. It is thus crucial to combine short-term and long-term goals. For manufacturing organizations to contribute to sustainable development, this requires long-term thinking hand in hand with short-term actions. It is widely recognized that a long-term perspective is essential for manufacturing organizations. For example (Kopac, 2009), argues that a long-term business strategy is essential to achieve sustainable development. However, our analysis of articles shows that only five out of 189 articles explicitly mention the time perspective (Fig. 5). Two articles emphasize the need to focus on both long and short-term thinking, and four articles discuss only long-term aspects without mentioning the short-term aspects.

The reviewed data shows that the time perspective is rarely a part of the definitions of SM. This may imply that long-term thinking is not a predominant consideration among researchers regarding SM. Failing to address the importance of long-term focus can influence the operationalization of the SM concept as industry leaders tend to focus on short-term issues rather than longer-term issues (O'Regan and Ghobadian, 2004), and short-term performance is frequently prioritized over long-term performance (Rappaport, 2005).

3.4. Integrating perspective

The concept of integration means combination, connection or incorporation of elements or activities. In the context of SM, two types of integrations prevail: integration of business elements, and integration of sustainability dimensions with business elements.

Integration of business elements includes the integration of elements such as a product, process, systems, strategy, function, etc. Research on organizational integration can be traced back to 1980s when researchers started to understand the role of integration in manufacturing (Turkulainen and Ketokivi, 2012). state that organizational integration is one of the most established concepts in the study and practice of operations management, which has been addressed in different contexts such as supply chain integration, plant location decisions and subsequent integration within a firm's plant network, and cross-functional integration. Organizational integration is commonly discussed in terms of improved manufacturing performance. For example (Burbidge et al., 1987), see integration as a method to improve the efficiency of a manufacturing organization. They recommend four types of integration in manufacturing organization: integration of goals, integration of plans within each function, integration of plans between functions, and systems integration. Similarly (Teixeira et al., 2012), conclude that cross functional integration can help achieve better performance in terms of innovation, quality, etc (Jawahir et al., 2013). argue that integration of product, process and system levels must ultimately enable sustainable value creation for all stakeholders (Ettlie and Reza, 1992). study organizational integration and process innovation, concluding that the following integrating mechanisms can help an organization capture the value from process innovations: (1) hierarchical structure; (2) increased coordination between design and manufacturing; (3) greater supplier cooperation; and (4) forming of new customer alliances.

Integration of sustainability concerns with business elements has been widely researched and is seen as a means to pursue sustainability in manufacturing organizations. The literature covers integration of sustainability perspectives (e.g., environmental issues, social responsibility, full sustainability) with different types of business elements, such as manufacturing strategy (Ocampo and Clark, 2017), product design, manufacturing, and delivery decisions (Waage, 2007), product development processes (Brones et al., 2014), and process design (Azapagic et al., 2006). Integration of sustainability into the product and process development requires development of new models, frameworks, metrics, and techniques (Molamohamadi and Ismail, 2013). However (Jamali, 2006), argue that it is impractical to prescribe one single and all-encompassing formulae for integration of Triple Bottom Line (TBL) into a diversity of organizations and sectors. Some authors also state that implementation of sustainability requires integration of a sustainability vision into strategies, practices and measurement systems. Many researchers have called for integration of sustainability and business elements, such as a business model, strategy, product, process, and decision-making (Petrini and Pozzebon, 2010). argue that there is a strong relation between integration of sustainability into a company's business practices and its organizational change toward sustainability. (Hall and Wagner, 2012), who studied an association of the integration of strategic issues and environmental management with the economic and environmental performance of firms, found a positive correlation between the integration of strategic issues and environmental management for both product and process innovation.

The result of the content analysis made herein shows that only one article considers the integration of business elements, where business models, products, services, systems, and customers are considered as an integral part of an organization. Eight articles focus on the integration of different aspects of sustainability or TBL with business elements such as processes, decision-making, value creation, manufacturing procedures, company's business processes and decisions, production, technological and organizational measures within the normative, strategic and operative production management, and operational and business activities.

It can be concluded that although both organizational integration and integration of sustainability with organizational elements are widely discussed as a means to improve organizational performance, it is only slightly touched by a few authors according to our results.

3.5. Triple bottom line

TBL has been put on the global agenda by Elkington in 1997 (Elkington, 1997). Since then companies have attempted to apply the TBL framework as a way to reduce the complexity of the sustainability concept. The content analysis conducted herein identified 33 articles that mentioned TBL in the definition of SM, representing less than 18% of the analyzed articles.

3.6. Relation between sustainability and manufacturing

Many researchers have discussed the relation between sustainability and manufacturing since the latter is considered as both a threat and solution to the former (see, e.g (Molamohamadi and Ismail, 2013; Rosen and Kishawy, 2012).,). Sustainable production is one of the Sustainable Development Goals (SDG) set by UN in 2015, which defines manufacturing as one of the measures toward sustainable development. While manufacturing has negative impact on the environment, it also creates jobs and has a positive contribution to the population's needs for food, shelter, healthcare, as well needs for comfort and decent level of life. Also, the manufacturing sector is important for sustainable development of the global society since it helps addressing global challenges such as needs for renewable energy sources, green buildings, etc.

In our content analysis, two sub-categories have been defined: manufacturing for sustainability and sustainability of manufacturing. 24 of the articles identified state that manufacturing contributes to a (more) sustainable society with the aid of sustainable products (manufacturing for sustainability). 23 articles present the idea of sustainability of the manufacturing sector (Fig. 6).

In addition, we found that the definitions in six articles explicitly state that SM is a part of the sustainable development concept, e.g., "based on the idea of sustainable development" (Chen and Zhang, 2009), "branch of sustainability" (Valaki et al., 2016), "a key component of sustainable development (Loglisci et al., 2013).

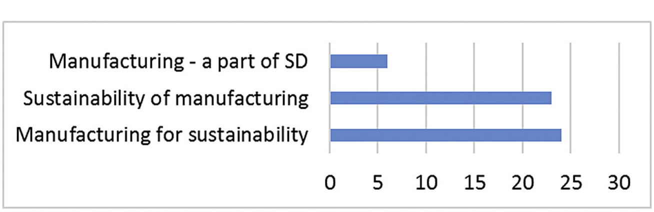

Fig. 6. Number of articles that include 'relation between sustainability and manufacturing' in a definition of sustainable manufacturing.

3.7. Domains

In SM, different focus domains for actions can be outlined, including *product*, *process*, *technology*, *supply chain*, *organization (as a whole)*, *employees, and customers*. Actions or efforts are usually applied to the various domains in order to influence performance characteristics. For example, *a practice* can be applied to improve safety, *a product* can be developed to reduce resource use, actions are undertaken to satisfy *customers*, etc. Here, *'practice'*, *'product'*, and *'customers'* are domains, while 'safety', 'reduction of resource use', and 'satisfaction' are performance characteristics.

This content analysis reveals fifteen different domains, in which *product, process, community, employees*, and *customers* are the most frequently mentioned ones (Fig. 7). For example, the following definition includes four domains: "use *processes* that minimize negative environmental impacts; conserve energy and natural resources, are safe for *employees*; *communities*; and *consumers* and are economically sound" (Jasiulewicz-Kaczmarek, 2013).

3.8. Potentials to enhance

'Potentials to enhance' (see Fig. 8) can be seen as something that organizations want to improve by maximizing or increasing, including reliability, productivity, safety, quality, etc. In this connection, the content analysis shows that natural environment, economic benefits, and safety are the most frequently used potentials to enhance in the various definitions of SM.

Economic benefits are mentioned in 124 articles, of which 114 articles focus on the *process* domain; for example, "processes that are economically sound". Fewer definitions focus on the economic benefits at the *product, services* and *organization* domains.

Even though politicians and developers have used sustainable growth as a synonym for sustainable development (Ulhoi and Madsen, 1999), it is essential to move from a 'traditional growth

Fig. 7. Number of articles that include 'domains' in a definition of sustainable manufacturing.

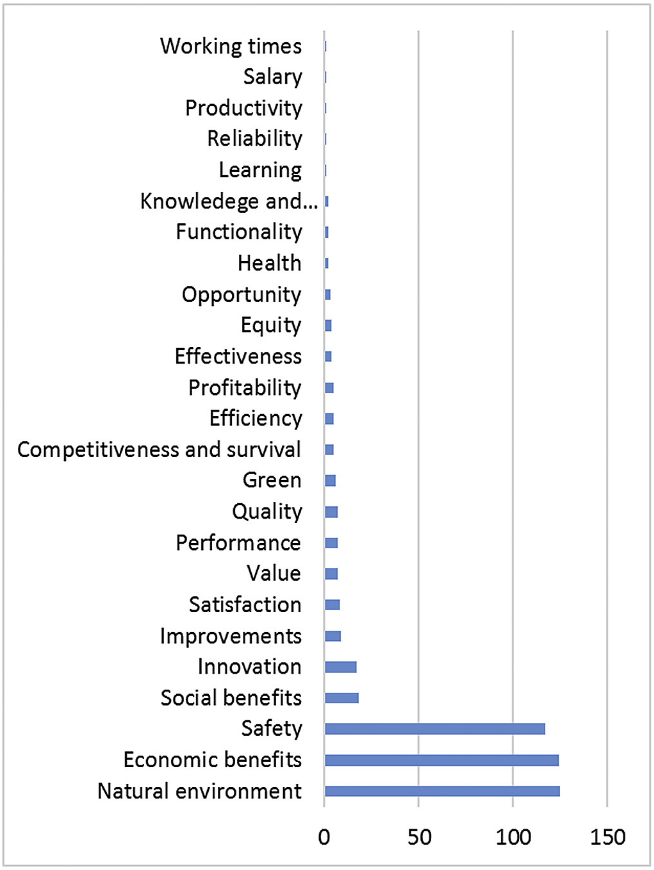

Fig. 8. Number of articles that include 'potentials to enhance' in a definition of sustainable manufacturing.

philosophy' to 'development within the environmental boundaries'. Our content analysis, however, indicates that only a few articles highlight growth as an economic benefit (Chen and Zhang, 2009; Khoo et al., 2001; Ocampo et al., 2015; Ocampo and Ocampo, 2015).

The natural environment has been included in this category since manufacturing can enhance the natural environment by decreasing its negative impact. Four categories are distinguished as to how researchers refer to the impact on the natural environment:

- the term 'minimize' the impact (and synonyms as reduce, etc.);
- the term 'has minimum impact';
- the term 'has no impact'; and
- positive focus as to improve environmental friendliness or stewardship; maximize environmental returns; respecting the environment, etc.

One important issue in this connection is to identify which of the four formulations that can provide (most) valuable information for decision makers. If one of the SM criteria is to minimize the impact on the environment, then even a minor reduction will count. If the criterion is to have a minimum impact, then it is necessary to define and quantify minimum impact. When the criterion is to have no impact, the question is whether this is real and whether this criterion will help to choose between two alternatives (technologies, products, etc.) when both clearly will have some impact. Also, criteria as 'respecting the environment' or 'improving environmental friendliness' can be too vague for decision makers to use in practical implementation.

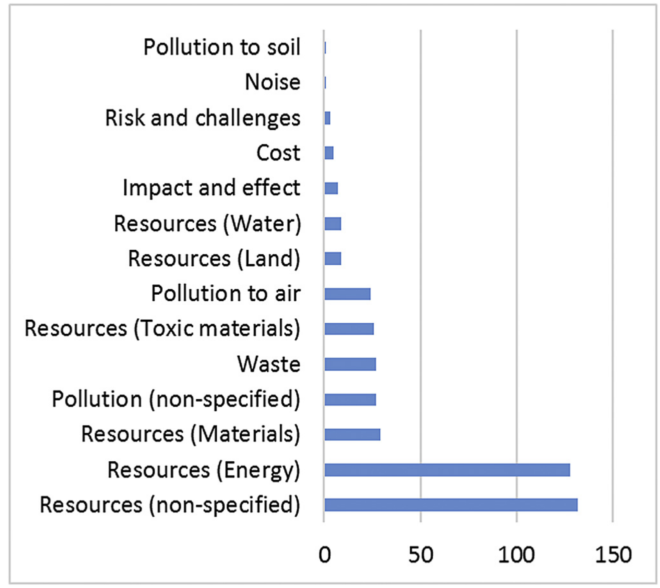

Fig. 9. Number of articles that include 'potentials to decrease' in a definition of sustainable manufacturing.

3.9. *Potentials to decrease*

The category 'potentials to decrease' includes those issues that an organization can improve by decreasing or mitigating; e.g., pollution, waste, noise. Fig. 9 lists, among others, six sub-categories addressing natural resources: water, land, materials, toxic materials, energy, and non-specified resources (when the definition includes terms as 'reducing resource use'). *Resources (non-specified)* and *resources (energy)* are the most frequently used terms in the definitions, appearing in more than 100 articles.

Two different views are identified when authors refer to *pollution to air*, *pollution (non-specified)*, *resources (toxic materials)*, *waste, and resources (non-specified)*. Some articles use the word 'reduction', e.g., reduction of emission. Other articles, on the other hand, focus on the *desired level*; e.g., without emission. Moreover, some authors use formulations that are more easy to use as a guide in practice; examples are given as 'minimize resource consumption', 'utilize minimum resources'. Other authors use more vague phrases such as 'smartly use natural resources' or 'optimized use of resources'.

3.10. *Other*

Phrases used in the definitions failing to fall within the nine categories above have been grouped in a category denoted 'Other', including:

- "maintain its [organization] internal structure" (Ngan et al., 2001).
- "for all technological and organizational measures within the normative, strategic and operative production management" (Herrmann et al., 2008).
- "[a paradigm] that manages and uses all direct and indirect information, process, and activities [related to the products,

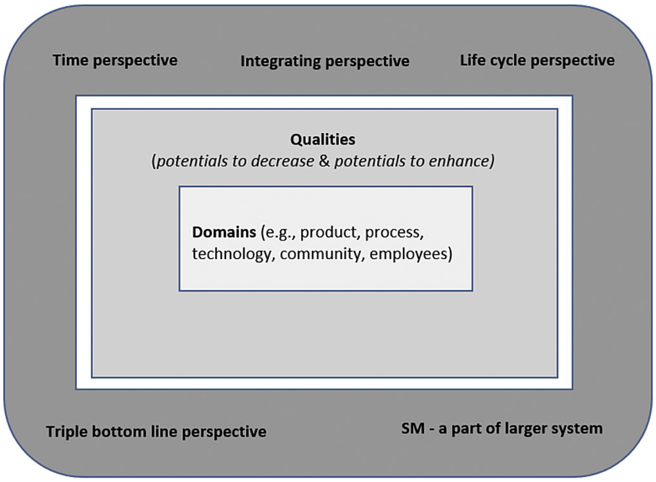

Fig. 10. Understanding of SM extracted from definitions.

processes, resources, and plants within the entire closed-loop product life cycle]" (Lee et al., 2014).

- "taking a high level view of manufacturing" (Smith and Ball, 2012).
- "eco-design" (Abullah et al., 2015).

3.11. SM framework based on the content analysis

Based on the result of the content analysis, a framework for the SM concept can be developed. The framework illustrates the understanding of the concept by the researchers attempting to define SM. The framework (Fig. 10) consists of (1) fundamental views that researchers see as important when practicing sustainable manufacturing, (2) application domains, e.g., product, process, customer, employees, etc., which are the focus of the actions, and (3) qualities of interest for different domains. The framework represents the categories identified during the content analysis, organizing them into the three groups.

4. Concluding remarks

Although gaining increased attention in research and industry, the definitions of SM remain inconclusive within the research community (Wang et al., 2016). Thus, the main question is if there is a unified understanding of its content, despite the number of interpretations prevailing in the literature.

4.1. Claim 1: There is a wide deviation from the core understanding of the SM concept, i.e., number of issues associated with SM

In this paper, a systematic literature review was conducted to identify definitions used in the literature in the period 1990 through 2016. The result of content analysis shows that 89 different definitions have been used to describe SM in 189 articles.

The different definitions varied in their coverage and fell into nine categories. More than 100 articles were found to cover eleven sub-categories, including product, resources (non-specified), resources (energy), process, production/creation, natural environment, economic benefits, community, safety, employees, and customers. Each of the remaining (67) sub-categories has been presented in less than 34 articles. Our chronological analysis showed that most of the sub-categories have emerged after 2008 when U.S. Department of Commerce published its renowned definition of SM. However, about 25% of the sub-categories were already mentioned in articles before 2008. 63% of the analyzed articles cite or slightly rephrase the definition of U.S. Department of Commerce, while 86% of identified articles are used in less than three articles.

Other inconsistencies have also been identified; e.g., 22 out of 25 'potentials to enhance' are mentioned in less than 24 articles, and twelve out of fourteen 'potentials to decrease' are mentioned in less than 30 articles.

The vast majority related SM to product, process, community, employees, and customers. The rest has related SM to a wide range of other domains such as stakeholders, technologies, services, supply chain, etc. Moreover, there are inconsistencies associated with the understanding in the use of life cycle perspective, time perspective and integrating perspective. It is noteworthy that less than 10% of the articles include these issues in the definition.

It can be concluded that the eleven sub-categories used in the majority of articles represent the *core understanding* of the content of SM. However, the use of other 67 sub-categories indicates that there is a wide deviation in the core understanding, which means that a unified understanding is not reached yet.

4.2. Claim 2: There is inconsistency in the understanding of issues associated with SM concept, i.e., content of issues associated with SM

Our analysis showed that there are many differences between the definitions used in the literature—some minor and some major. The former takes place in the use of synonyms such as 'reduce' and 'minimize', 'avoid' and 'mitigate'. The latter leans towards the terms defining SM such as 'strategy', 'practice', 'system', or 'technology'.

The understanding of SM as a concept among researchers differs, particularly concerning the impact on the natural environment, where four approaches have been identified. Similar differences have also been identified concerning pollution, waste, and resources use. Some definitions include terms that are more ambiguous such as 'smartly use natural resources', while other definitions are more precise, e.g. 'minimize resource consumption'.

It can be concluded that inconsistency in the understanding of issues associated with the SM concept results in the lack of a unified terminology and vocabulary.

4.3. Claim 3: There is a mix of performance-related features and sustainability-oriented instruments in the definitions of the SM concept

Our analysis revealed that when researchers define SM, both sustainability performance characteristics and organizational instruments, aimed at operationalizing sustainability in manufacturing, are used to describe SM. Both 'potentials to enhance' and 'potentials to decrease' can describe the actual sustainability performance of an organization. On the other hand, application of 'life cycle perspective', 'time perspective', 'integrating perspective', addressment of *TBL* issues, and focus of efforts for different *domains* can be seen as measures for achieving organizational sustainability performance (Schneider and Meins, 2012). argue that it is important to differentiate between actual contribution of an organization to sustainability, and sustainability-oriented organizational structures and managerial instruments, which in itself does not guarantee sustainability performance. However, our analysis showed that researchers include both matters when describing SM. Thus, there is a risk that organizations will denote their practices as ‘sustainable manufacturing’ when simple sustainability-oriented practices are implemented.

Our analysis highlights the consistencies and inconsistencies in the research community related to the definitions and interpretations of SM. Our hope is that the findings in this study can stimulate to further discussions and thus make a contribution towards the development of a common language for SM, both as a research field and as an industrial practice.

The authors see the variety of sustainable manufacturing definitions as a barrier for further development of the industry. Acceptance of many definitions and interpretations of the concept can lean the concept towards the perceptions of the one who defines it. In other words, some actions that do not lead to sustainability might be hidden behind some interpretations or definitions of sustainable manufacturing. Although we recognize that continuous knowledge creation will lead to the modification of the understanding of SM as a concept, we argue that it is crucial to establish the core criteria of SM to avoid misinterpretation of the concept depending on the preferences of the individual actors. Moreover, we suggest that a ‘systems view’ is missing in all analyzed definitions and should be pursued when working with sustainable manufacturing. It should (to a larger extent) be recognized that the company is a part of the larger system, in addition to being a complex system by itself. As our analysis shows, SM is associated with a variety of application domains and issues for improvements. Thus, a systems view will help ensure that the organization is not pulled in different directions, ones that sometimes might be conflicting.

The analysis presented in this paper enabled the authors to define ‘sustainable manufacturing’ by using the concept of attractor as a metaphor. Sustainable manufacturing is thus defined in (Moldavska and Martinsen, in press) as a complex behavior pattern to which any manufacturing organization should tend to evolve. This behavior pattern is defined by the criteria for SM, which were defined by the authors based on the result of the content analysis presented herein.

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Appendix A. Coding of sustainable manufacturing definitions

Category	Sub-category	Articles	Examples
1. Terms defining “sustainable manufacturing” concept	Production/Creation	126	e.g., “creation of manufactured products”, “creation of goods and services”, “producing products”, “process of manufacturing”
	Approach/Strategy	20	e.g., “a comprehensive business strategy”, “a positive business approach”, “a systems approach”
	Practice	10	e.g., “the practice of developing products, processes, and services”, “practicing technologies”, “a business practice”
	Paradigm	8	e.g., “a new necessary paradigm”, “a new manufacturing paradigm”
	System	8	e.g., “systems of production”, “a manufacturing system”
	Ability	5	e.g., “the ability to smartly use natural resources”, “the ability of a company to innovate”
	Instance of another field of science	5	e.g., “an instance of sustainable engineering”, “a part of sustainable production”
	Develop/Design	7	e.g., “developing technologies”, “design products”
	Solutions	3	e.g., “a set of technical and organizational solutions”,
	Technology	2	e.g., “technology of manufacturing”, “the innovative technology”
	Other	8	e.g., “an effort to improve the production process”, “the science of manufacturing”, “set of systems and activities”, “vision”
2. Life Cycle Perspective	Total life cycle	18	e.g., “total life cycle issues”, “the entire life cycle of the product”, “the entire product and service life cycle”
	Life cycle issues	8	e.g., “across the lifecycle of product”, “lifecycle issues of product”
	Closed loop	2	e.g., “entire closed-loop product life cycle”, “closed loop supply chain”
	End of life	8	e.g., “recycling capability”, “remanufacturing”, “end-of-life management”,
3. Time perspective	Short term and Long term thinking	2	e.g., “short term and long term”, “now and in the future”
	Long term thinking	4	e.g., “long term existence”, “strives for a long-term global competitive advantage”
4. Integrating perspective	Integration of business elements	1	e.g., “to include business models, product, services, systems, and customers as integral part”
	Integration of business elements with TBL aspects	8	e.g., “integration of processes, decision making and the environmental concerns”
5. TBL (Triple bottom line)	TBL aspects	33	e.g., “full sustainability”, “environmental, social and economic aspects”, “environmental stewardship, economic growth, and social well-being”
6. Relation between sustainability and manufacturing	Manufacturing - a part of SD	6	e.g., “based on the idea of sustainable development”, “a significant key to sustainable development”
	Manufacturing for sustainability	24	e.g., “manufacturing of ”sustainable“ products”, “contributing to the global society's ability to address sustainability issues”
	Sustainability of manufacturing	23	e.g., “produce in a sustainable manner”, “sustainable manufacturing of all products”, “sustainability of manufacturing sector”
7. Domains	Community	119	e.g., “safe for communities”, “being a responsible member of the community”, “respecting communities' wellbeing”
	Customers	105	e.g., “safe for consumers”, “satisfy customer needs”
	Employees	117	e.g., “safe for employees”, “social responsibility for employees”
	Stakeholders	2	e.g., “responsive to the social needs of relevant stakeholders”, “impacts to various stakeholders”
	Techniques	4	e.g., “environmentally sound techniques”

(*continued*)

Category	Sub-category	Articles	Examples
	Methods	4	e.g., “implementation of innovative methods”, “manufacturing methods utilising … ”
	Organization	7	e.g., “economic life of a particular firm”, “better firm performance”
	Practices	4	e.g., “socially sensitive practices”, “more sustainable practices”
	Solutions	9	e.g., “creating solutions”, “develop solutions to design”
	Technologies	21	e.g., “developing technologies”, “use technologies that … ”
	Product	154	e.g., “creation of manufactured product”, “distribution of innovative products”, “environment-friendly products”
	Process	127	e.g., “process that minimizes negative environmental impact, …”, “use process that … ”
	System	13	e.g., “creation of products with systems that … ”
	Services	23	e.g., “creation and distribution of innovative services”
	Supply chain	12	e.g., “development of supply chain that conserves resources”
8. Potentials to enhance	Competitiveness and survival	5	e.g., “strives for global competitive advantage”, “maintaining economic competitiveness”
	Economic benefits	124	e.g., “maximizes the economic returns”
	Effectiveness	4	e.g., “maximization of effectiveness of each technical product”, improving its operational effectiveness"
	Efficiency	5	e.g., ”improving its operational efficiency", ”implementing resource efficiency"
	Equity	4	e.g., ”social equity-related products", “bringing social equity”
	Functionality	2	e.g., “fulfilling their functionality over the entire lifecycle”, “satisfies (social) demand for functionality”
	Health	2	e.g., “eliminate agents hazardous to human health”, “viability of workers health”
	Improvements	9	e.g., “finding points along the supply chain where improvements can be made”, “improving processes and products”
	Innovation	17	e.g., “innovative techniques”, “innovative products and services”
	Knowledge and competence	2	e.g., “improve one's professional knowledge and competence”
	Learning	1	e.g., “opportunity of learning”
	Opportunity	3	e.g., “maximising the new opportunities”, “providing opportunities for company economic and environmental sustainability”
	Performance	7	e.g., “lead to superior sustainability performance”, “lead to better firm performance”
	Productivity	1	e.g., “productivity growth”
	Profitability	5	e.g., “operate profitably”, “improve their company's profitability”
	Quality	7	e.g., “to improve the quality of human life”, “produces high quality products”
	Reliability	1	e.g., “maintaining the reliability of products and services”
	Safety	117	e.g., “process that are safe”, “enhances safety for employees”
	Salary	1	e.g., “dignitous salary”
	Satisfaction	8	e.g., “satisfy customer needs”, “work seen as a mix of …, satisfaction, … ”, “satisfy economical, environmental and social objectives”
	Social benefits	18	e.g., “remain socially beneficial”
	Value	7	e.g., “system that produces value”, “conversion of resources into value for society”
	Working times	1	e.g., “acceptable working times”
	Green	6	e.g., “activities that are considered green”, “green building”, “green products”
	Natural environment	125	e.g., “minimize negative environmental impacts”, “respecting Earth‘s carrying capacity”, “preserving the environment”
9. Potentials to decrease	Cost	5	e.g., “delivering products at a lower cost”, “products at an affordable cost”
	Noise	1	e.g., “reducing the noise”
	Pollution to air	24	e.g., “without emission of greenhouse gases”
	Pollution to soil	1	e.g., “sends nothing to landfill”
	Pollution (non-specified)	27	e.g., “releases no pollutants”
	Impact and effect	7	e.g., “provide society with goods that fulfil a task with minimum impact”
	Resources (non-specified)	132	e.g., “without destroying precious resources”, “manufactured with optimized usage of resources”
	Resources (Toxic materials)	26	e.g., “reduction in use of toxic materials”
	Resources (Energy)	128	e.g., “processes that conserve energy”
	Resources (Land)	9	e.g., “minimizes inputs such as land”
	Resources (Water)	9	e.g., “minimizes inputs such as water”
	Resources (Materials)	29	e.g., “without use of non-renewable materials”, “minimize resources as materials”
	Risk and challenges	3	e.g., “coping with recent challenges and problems”
	Wastes	27	e.g., “without generation of waste”, “produces zero waste”
10. Other	Other	5	e.g., “maintaining its internal structure”, “for all technological and organisational measures within the normative, strategic and operative production management”, “manages and uses all direct and indirect information, processes, and activities”, “taking a high level view of manufacturing”, “eco-design”

Appendix B. Chronological analysis of sub-categories

Sub-categories	Number of articles	1996	1997	1998	1999	2000	2001	2002-2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
7. Product	154								3	4	8	8	20	19	24	44	24
9. Resources (non-specified)	132						1		2	3	6	8	17	18	24	35	18
9. Resources (Energy)	128								1	3	7	8	15	18	24	35	17
7. Process	127	1					1		1	3	5	6	15	18	23	38	16
1. Production/Creation	126									2	6	8	17	17	22	36	18
8. Natural environment	125				1		2		1	4	4	7	16	13	19	37	21
8. Economic benefits	124				1		1			5	6	8	14	17	22	32	18
7. Community	119									3	5	8	16	16	22	31	18
8. Safety	117									2	5	8	15	16	23	31	17
7. Employees	117								2	2	5	8	15	15	22	31	17
7. Customers	105									1	5	8	16	14	20	28	13
5. TBL	33								1	1	1		3	3	2	13	9
9. Resources (Materials)	29									1	4	1	3	6	6	7	1
9. Pollution (non-specified)	27				1					2	3	1	2	6	5	4	3
9. Waste	27									1	3	1	3	6	6	7	
9. Resources (Toxic materials)	26									2	3	1	2	6	6	6	
6. Manufacturing for sustainability	24									1	2	2	5	2	4	5	3
9. Pollution to air	24									1	3	1	3	4	6	6	
7. Services	23								3	1	2		1	4	5	6	1
6. Sustainability of manufacturing	23									1	2	2	5	2	4	4	3
7. Technologies	21									1	2	1	2	4	4	6	1
1. Approach/Strategy	20				1					1	3		2	3	3	5	2
8. Social benefits	18						1		2	1	2		1	1	3	5	2
2. Total life cycle	18									1	2		1		4	8	2
8. Innovation	17				1						1			1	4	8	2
7. System	13						1		1	1	1			1	1	6	1
7. Supply chain	12										1				4	7	
1. Practice	10								1	1	1	1		1	1	2	2
7. Solutions	9									1			1		1	5	1
9. Resources (Land)	9										1				3	4	
9. Resources (Water)	9										1			1	3	4	
8. Improvements	9	1												1	3	2	2
4. Integration of business elements with TBL	8						1					1	1	1	1	2	1
8. Satisfaction	8												2	2	1	1	2
2. Life cycle issues	8								1				1	1	1	4	
2. End-of-life	8				1					2						3	2
1. Paradigm	8								1				1	3	2	1	
1. System	8								2					1	2	2	1
1. Other	8	1								1						5	1
8. Performance	7												1	1	2	2	1
9. Impact and effect	7								1					1	1	2	2
8. Value	7								2		1			1	1	1	1
8. Quality	7												1		3	1	2
1. Develop_design	7									1	1			2	2	1	
7. Organization	7											1		1	1	2	2
6. Manufacturing - a part of SD	6									1				3	1		1
8. Green	6								1		1				1	2	1
8. Cost	5									1					1	3	
8. Competitiveness and survival	5						1						1	1	2		
8. Efficiency	5										1				1	2	1
8. Profitability	5						1								1	1	2
1. Ability	5												1		1	1	2
1. Instance of other field of science	5									1	1		1			2	
10. Other	5						1		1				1		1	1	
7. Practices	4										1				1	1	1
8. Effectiveness	4								1					1	1		1
8. Equity	4										1				1	1	1
7. Techniques	4				1									1	1	1	
7. Methods	4															4	
3. Long term thinking	4						1							1		1	1
8. Opportunity	3													1		1	1
9. Risk and challenges	3												1		1	1	
1. Solutions	3															3	
8. Functionality	2								1						1		
8. Health	2													1		1	
8. Knowledege and competence	2									1				1			
7. Stakeholders	2														1	1	
2. Closed loop	2														1	1	
3. Short term and Long term thinking	2						1								1		
1. Technology	2									1							1
4. Integration of business elements	1															1	
8. Learning	1													1			
8. Productivity	1																1
8. Reliability	1														1		
8. Salary	1													1			
8. Working times	1													1			
9. Noise	1															1	
9. Pollution to soil	1				1												

Appendix D. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.08.006.

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