Journal of Cleaner Production xxx (2014) 1–12

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A framework for a research inventory of sustainability assessment in manufacturing

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ARTICLE INFO

Article history:
Received 4 June 2013
Received in revised form
10 April 2014
Accepted 4 May 2014
Available online xxx

Keywords:
Classification scheme
Research inventory
Sustainability in manufacturing
Sustainability assessment in manufacturing

ABSTRACT

Numerous research papers have focused on the development of guidelines, indicators, metrics, methods, tools, and systems for sustainability performance assessment. However, manufacturing companies have had difficulty identifying those papers that are relevant to their desires to assess and improve the sustainability of their plants. A research inventory, a data repository for storing papers in a manner that makes them easy to retrieve, could be a tool to address this issue. To be successful, the inventory must have a system for organizing, indexing, and managing the results generated by a large number of researchers from around the world. In this paper, we propose a framework for a research inventory that focuses on papers related to sustainability assessment in manufacturing. The framework consists of two parts: an operational definition to distinguish between papers that belong in the inventory and those that do not, and a classification scheme to allow papers to be efficiently retrieved. We developed a prototype of the research inventory and its search engine based on the proposed framework. This paper demonstrates the prototype with three reference papers. The results show that our classification scheme expresses key meta-information that provides a basis for the search engine to identify the most suitable papers for the selected conditions. This meta-information is a significant improvement over the traditional indexing schemes used to search for journal papers. Our framework will enable the research inventory to be searched for the most relevant papers in an easy and practical way. Consequently, we believe that the proposed framework and inventory will be more useful for manufacturing companies trying to use the latest research results to improve their sustainability assessments and impacts.

1. Introduction

To ensure their long-term survival in global markets, manufacturing companies must pursue sustainability as a strategic goal. A prerequisite for this pursuit is the ability to perform a sustainability assessment of their products and processes (Rosen and Kishawy, 2012; Garetti and Taisch, 2012). Such an assessment includes both a sustainability accounting and an impact analysis. Sustainability accounting involves measurements of resource utilization, waste generation, and pollution emission from all activities in manufacturing. Impact analysis evaluates the impact of those measurements on the public's wellbeing, on the environment, and on the economy (Feng et al., 2010). Measurements must use predefined performance metrics and scientific methods for computing them. Impact analysis must be compared against accepted industry benchmarks. While metrics, methods, and benchmarks are abundant in the assessment literature (Singh et al., 2012), it is often difficult for manufacturing companies to find and use the ones most relevant to their industry and company goals (Poveda and Lipsett, 2011).

To overcome this difficulty, we recommend the creation of a research inventory of sustainability assessment in manufacturing. The research inventory contains (1) a repository of papers related to sustainability assessment in manufacturing and (2) a system for managing those papers. The management system provides four major functions: identifying which papers are relevant; classifying and tagging papers with meta-information sufficient for identification and retrieval; archiving papers in a repository; and responding to queries for specific papers using the meta-information. Through using these functions, the inventory will enable users to get a better understanding of the current research

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http://dx.doi.org/10.1016/j.jclepro.2014.05.004
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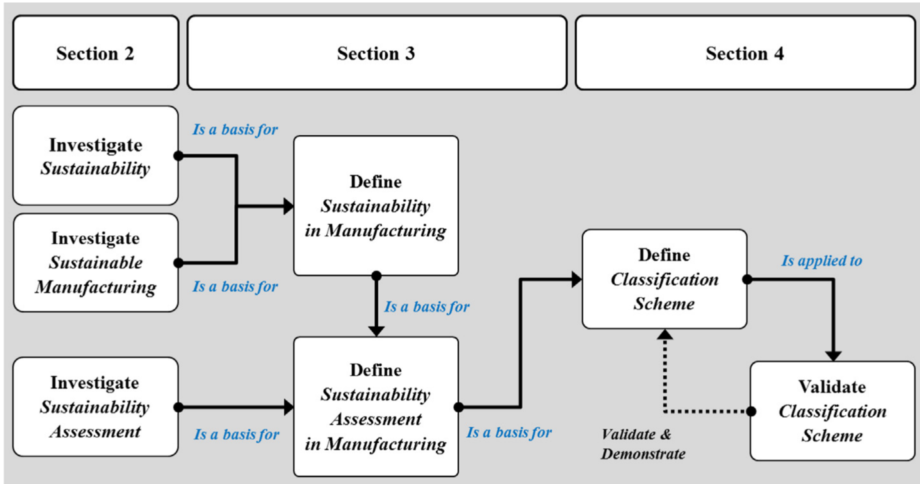

Fig. 1. Main research tasks and their relationships for the paper.

landscape. It will also enable researchers to identify gaps and conduct new investigation to fill those gaps.[2]

This paper focuses on developing a research inventory for papers that address methods[3] related to sustainability assessment in manufacturing to support the management functions described above. It proposes an operational definition for identifying relevant papers and a scheme for classifying and tagging those papers. The definition describes concepts and terminologies associated with papers on sustainability assessment in manufacturing. The classification scheme provides a taxonomy for classifying those papers. Together, these components make up the framework for our inventory.

The details of that framework are described in the remainder of the paper. Section 2 summarizes other inventories and a variety of commonly used definitions of sustainability, sustainability assessment, and sustainable manufacturing, and reviews the literature on classification schemes. Section 3 provides the definitions that we use for admission into the repository. Section 4 describes the taxonomy that we will use for our classification scheme with its notation for methods to assess the sustainability in manufacturing. A prototype of the research inventory and its search engine was implemented based on the framework proposed in the paper and is also demonstrated with existing methods in Section 4. Section 5 summarizes contributions and future work. The approach for this paper is depicted in Fig. 1, which shows main tasks and their relationships.

2. Literature review

This section investigates relevant literature on research inventories, definitions of sustainability, sustainability assessment, and sustainable manufacturing, and classification schemes.

2.1. Research inventories

A variety of research inventories have been developed in accordance with their target research field and scope. For example, the European Science Foundation developed a portal called MERIL (Mapping of the European Research Infrastructure Landscape), which is a comprehensive inventory of research of major relevance in Europe across all scientific domains and is accessible to the public through an interactive online portal (ESF, 2013). Some universities developed their own inventories to manage research efforts for sustainability for their faculty members. For example, the Institute for the Environment of the University of North Carolina (UNC) developed a sustainable research inventory that provides a comprehensive inventory of sustainability-related research initiatives (UNC, 2010). The University of California, Irvine (UCI) defined the concept of sustainability research and established the sustainability research inventory that identifies their activities and facility engaged in such activities (UCI, 2013). The University of New Hampshire (UNH) Sustainability Research Inventory was also developed to manage their research efforts (UNH, 2010). The U.S. Environmental Protection Agency (EPA) developed the science inventory that is a searchable catalog of on-going and completed science activities and scientific and technical products conducted by EPA and EPA-funded universities and research institutes (US EPA, 2003). Through the literature review, we found that there exists no research inventory that focuses on methods for sustainability assessment in manufacturing.

Further investigation reveals that limitations exist with implementations of these research inventories. First, most inventories provide a simple list of papers. Only basic information (e.g., a title and authors) is provided for registration, tracking, and retrieving, like the inventory of EPA. Second, the target research field and scope of the inventory are often not clearly specified. For example, even though the UNH inventory is for sustainability research, the concept and scope of sustainability are not defined. Lastly, it is difficult to find a commonly accepted framework to implement a research inventory in a systematic manner. In many cases like the inventories of UNC and UCI, the inventories might satisfy specific purposes, however, no systematic implementation way was introduced. This could be the fundamental cause for the limitations in existing inventory schemes.

2.2. Defining sustainability

According to the World Commission on Environment Development (1987), sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” This was widely accepted as a formal definition of sustainable development

[2] The research inventory managed by the European Science Foundation (ESF, 2013) provides a similar capability for science.

[3] Method means all kinds of ways to assess sustainability, including tool, indicator, metric, etc.

Please cite this article in press as: Lee, J.Y., Lee, Y.T., A framework for a research inventory of sustainability assessment in manufacturing, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.05.004

(Baumgartner, 2011). In the ensuing years, more than 100 definitions of sustainability have appeared. While they differ in details, they all agree that sustainability aims to satisfy economic, environmental, and social goals (Labuschagne and Brent, 2005; MSA, 2008). These goals have come to be known as the three pillars or the triple bottom line (Earth Charter Initiative, 2000; Hardcastle and Waterman-Hoey, 2010).

According to the U.S. National Research Council (1999), sustainability is “the level of human consumption and activity, which can continue into the foreseeable future, so that the system that provides goods and services to the humans persists indefinitely.” The National Risk Management Research Laboratory of the U.S. Environmental Protection Agency suggested that “sustainability occurs when we maintain or improve the material and social conditions for human health and the environment over time without exceeding the ecological capabilities that support them” (Sikdar, 2003). Australia’s National Strategy for Ecologically Sustainable Development ecologically identified sustainable development as “using, conserving, and enhancing the community’s resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased” (ESDSC, 1992). According to Hediger (2000), sustainability is “a normative concept which involves trade-offs among social, ecological, and economic objectives, and is required to sustain the integrity of the overall system.” Lozano (2008) proposed the Two Tiered Sustainability Equilibria (TTSE) adding a time aspect to the economic, environmental, and social aspects to explain sustainability. Do (2010) defined sustainability as “the development concept and approach that realize social justice, maintain natural environment, and pursue economic prosperity” with 3P (People, Planet, and Profit) and 3E (Equity, Environment/Earth, and Economy). Feng et al. (2010) described sustainability in development as “an organization’s ability to advance its economic state without compromising the environment and the social equity that provide the quality of life for all community residents, present, or future.” Glavic and Lukman (2007) clarified and classified the meaning and applications of fifty-one different terms and their definitions related to sustainability.

Despite different purposes and perspectives, most sustainability definitions refer to an ability to satisfy social, environmental, and economic goals. These goals, which have clear quantitative aspects to them, must be met on an ongoing basis. Consequently, the concept of sustainability is associated with sustainable development. Additionally, these definitions are usually accompanied with a variety of metrics, which imply the need for some types of assessment methods.

2.3. Defining sustainability assessment

The need for assessment was recognized more than forty years ago. When it was first introduced, its original focus was on environmental impacts only. As the sustainability definitions gradually expanded to include social and economic goals, assessment began to include the three pillars of sustainability (Pope et al., 2004). Since these definitions varied in detail, numerous assessment methods, across different disciplines, began to appear. In this section, we summarize several of these methods based on their date of publication.

Devuyst and Hens (2001) explained sustainability assessment as “a tool that can help decision-makers and policy-makers decide which actions they should or should not take in an attempt to make society more sustainable.” According to Verheem (2002), the aim of sustainability is to ensure that plans and activities make optimal contributions to sustainable development. Buselich (2004) proposed that sustainability assessments are “assessment of proposed initiatives (projects, policies, and plans) in terms of sustainability to determine the conditions under which approval would be given.” Ness et al. (2007) argued that sustainability assessment has increasingly become associated with the family of impact assessment tools consisting of Environmental Impact Assessment, Strategic Environmental Assessment, and EU Sustainability Impact Assessment. Hasna (2008) added a technological dimension to the triple bottom line and proposed that an integrated assessment is “to assess the social, environmental, technological, and economic dimensions of projects, policies, and programs.” The researchers provided the approaches to describe sustainability assessment. These approaches all aim to support decision making to satisfy social, environmental, and economic goals. Mainly, sustainability assessment demands clarity in two aspects: sustainability objectives and assessment methods.

In addition to describing specific assessments methods, a number of researchers have developed criteria for classifying those methods. Baumann and Cowell (1999) suggested an evaluation framework for comparing conceptual and analytical methods based on their methodological features; however, the framework was limited to methods used in environmental management only. Ness et al. (2007) provided a categorization approach that included a much broader range of methods than those considered by Baumann and Cowell. Kinderytė (2008) presented comparison criteria of methodologies for corporate sustainability assessment. Other researchers have proposed criteria classifying existing sustainability assessment research, but none of these criteria address manufacturing specifically. Pope et al. (2004) surveyed and categorized sustainability assessment methods. Finnveden and Moberg (2005) did the same for environmental assessment methods. Hasna (2008) and Singh et al. (2012) reviewed sustainability assessment methods. Gunasekaran and Spalanzani (2012) investigated and classified the literature available on Sustainable Business Development in manufacturing and services. Some of the criteria proposed by these researchers are applicable to sustainability assessment methods in general. We will describe and use those criteria in Section 4.

2.4. Defining sustainable manufacturing

Sustainability has been interpreted in many ways based on requirements from different application domains and objectives. Manufacturing is considered as one of the most important domains for achieving sustainable development. Implementing sustainability in manufacturing will surely be one of the most positive contributions to sustainability in general (Garetti and Taisch, 2012). For that reason, assessing the sustainability of manufacturing has become a more prominent goal in recent years. As with the preceding topics, there are a number of definitions of sustainable manufacturing.

The Lowell Center for Sustainable Production defined sustainable production as “the creation of goods and services using processes and system that are: non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for workers, communities, and consumers, and socially and creatively rewarding for all working people” (LCSP, 1998). The Institute of Manufacturing at the University of Cambridge stated that “sustainable manufacturing is … developing technologies to transform materials without emission of greenhouse gases, use of non-renewable or toxic materials, or generation of waste” (Allwood, 2005). The U.S. Department of Commerce defined sustainable manufacturing 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” (US DOC, 2009).

According to the National Council for Advanced Manufacturing in the U.S. (2009), sustainable manufacturing includes both the manufacturing of sustainable products and the sustainable manufacturing of all products. The former includes manufacturing of renewable energy, energy efficiency, green buildings, and other green products. The latter emphasizes the sustainable manufacturing of all products taking into account the total life cycle of those products. At the Sustainable Manufacturing Consulting, sustainable manufacturing was identified as "a business practice of the industrial sector, which expands all the company's processes and decisions into the social and natural environments it operates in and affects, with the explicit objective of reducing or eliminating any negative impact, while pursuing the desired level of technological and economic performance" (Leahu-Aluas, 2009–2010).

International organizations have also weighed in on sustainable manufacturing. The Organisation for Economic Co-operation and Development (OECD) stated that the general principle of sustainable manufacturing is to reduce the intensity of materials use, energy consumption, and emissions, and the creation of unwanted by-products while maintaining or improving the value of products to society and to organizations (OECD, 2009). According to the Intelligent Manufacturing Systems (2011), sustainable manufacturing aims at developing innovative methods, practices, and technologies in the manufacturing field for addressing worldwide shortages of resources, for mitigating excess environmental load, and for enabling an environmentally benign life-cycle of products.

Given that there are multiple descriptions for sustainable manufacturing, it is not clear how the concept of sustainability in manufacturing is derived from sustainable manufacturing. One difficulty is that most existing definitions are at a conceptual level and do not include the components of production at a factory. Even though such definitions try to envision/describe how the concept of sustainability affects manufacturing, they are not viewed from a manufacturing engineering perspective. One way to differentiate the concepts is that sustainable manufacturing is a description of high level sustainability goals for a manufacturing company (e.g., the company should use as little water and produce as little CO_2 as necessary), whereas sustainability in manufacturing means the targets and approach for measurement to meet the high level goals within a manufacturing company (e.g., water usage and CO_2 produced at each stage of production will be measured and archived.) Section 3 addresses sustainability in manufacturing and its assessment in more detail.

3. Operational definitions for the inventory

None of the preceding definitions are directly applicable to our goal of developing a framework for an inventory of research papers on sustainability assessment in manufacturing. In this section, we provide those definitions.

3.1. Requirements for an operational definition

An operational definition is a statement that describes how a particular variable is to be measured or how an object or condition is to be recognized (Prentice Hall Science Explorer, 2001). It identifies something (e.g., a variable, term, or object) in terms of the specific process or set of validation tests used to determine its presence and quantity (Sevilla et al., 1992; Adanza, 1995). That is, one defines something in terms of the three requirements associated with measuring it (Watt and van den Berg, 1995; Shoemaker et al., 2004). Those requirements are listed below.

- It has criteria or variables. An operational definition translates the verbal concept into corresponding criteria or variables that can be measured. The concept can be referred to as a variable since it can respond to differences in the real world by taking on varying values.
- It has operations. An operational definition contains one or more operations that measure the values of the criteria or variables. The operation, a mathematical or logical process, aims at converting a concept into quantifiable values for the criteria or variables.
- It must be practical. An operational definition provides the operations that contain specified sequence with specific rules so that anyone can repeat the process. It is in this sense that an operational definition is practical.

In summary, an operational definition removes the ambiguity from a concept by actually measuring variables related to that concept.

3.2. Operational definition for sustainability in manufacturing

Many existing definitions of sustainable manufacturing consider product, process, and system as main components (Jawahir, 2008; Jayal et al., 2010; Brindle and Pack, 2011). Similarly, we include product design, process plan, and production system in our definition of sustainability in manufacturing (SiM) and refer to them as the SiM-3P. A product design is a detailed specification of a manufactured item's parts and their relationships to the whole (Ertas and Jones, 1996; Kamrani and Salheih, 2002). A process plan is a sequence of manufacturing operations required to produce a product that conforms to the product design. A production system is the collection of resources, equipment, and tooling used to execute the processes in the process plan (Koho, 2010). Given these concepts, we describe SiM as below.

Sustainability in Manufacturing (SiM) is a measure of the manufacturing performance metrics for product design, process plan, and production system with respect to the environmental, economic, and social aspects of sustainability.

The operational aspect of this definition aims at the measurement of the impacts on the environment, economy, and society. Fig. 2 depicts the interrelationships among SiM, SiM-3P, and their metrics. These metrics are related to impacts associated with the three pillars of sustainability. In Section 3.3, we address the assessment of these impacts.

3.3. Operational definition for sustainability assessment in manufacturing

Sustainability assessment in manufacturing (SAiM) is defined based on the SiM definition as follows.

Sustainability Assessment in Manufacturing (SAiM) is a means to determine a value for a SiM metric, which is balanced for product design, process plan, and production system performances with respect to the environmental, economic, and social aspects of sustainability.

Fig. 3 depicts the relationships among the Product Design (PD), Process Plan (PP), and Production System (PS) and the Environmental (En), Economic (Ec), and Social (So) pillars. Table 1 shows all of the potential impact assessments that can be performed. Each row depicts one of the SiM-3P and each column depicts one of the pillars. Additionally, the table shows aggregated rows (PD_{SiM}, PP_{SiM}, and PS_{SiM}), aggregated columns (En_{Total}, Ec_{Total}, and So_{Total}), and a variable called SiM_{Point}. SiM_{Point} represents an aggregated balance among the impacts of the SiM-3P. This balance is achieved through

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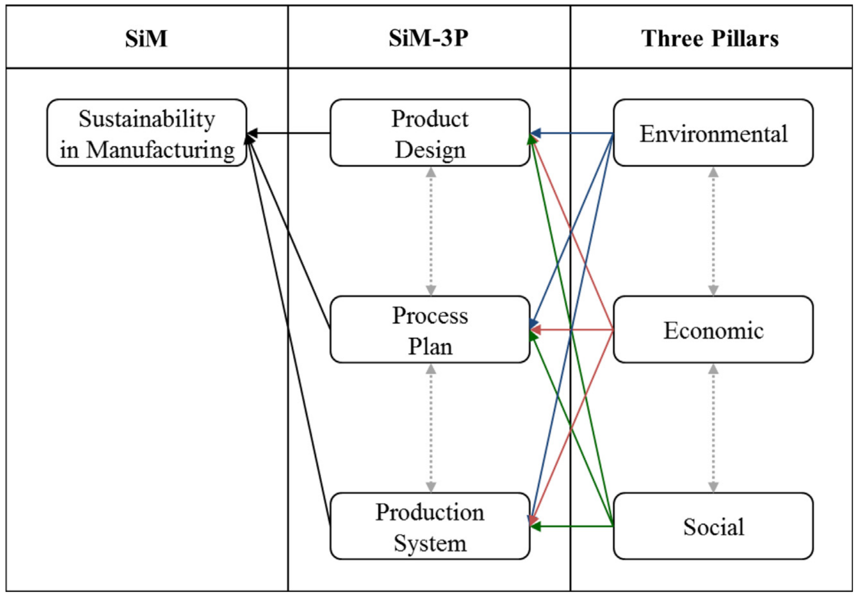

Fig. 2. Interrelationships among SiM, SiM-3P, and the three pillars.

a series of weights (e.g., W_{PD}) that can vary from one company to another.

Computing the total column's values (SiM_{Point}, PD_{SiM}, PP_{SiM}, and PS_{SiM}) is usually quite difficult since the metrics, associated with PD, PP, and PS, have different physical units. These computations can be formally represented as functions, F_i, as shown below.

$$SiM_{Point} = F(W_{PD}*PD_{SiM}, W_{PP}*PP_{SiM}, W_{PS}*PS_{SiM}) \quad (1)$$

$$PD_{SiM} = F_1(W_{PDEn}*PD_{En}, W_{PDEc}*PD_{Ec}, W_{PDSo}*PD_{So}) \quad (2)$$

$$PP_{SiM} = F_2(W_{PPEn}*PP_{En}, W_{PPEc}*PP_{Ec}, W_{PPSo}*PP_{So}) \quad (3)$$

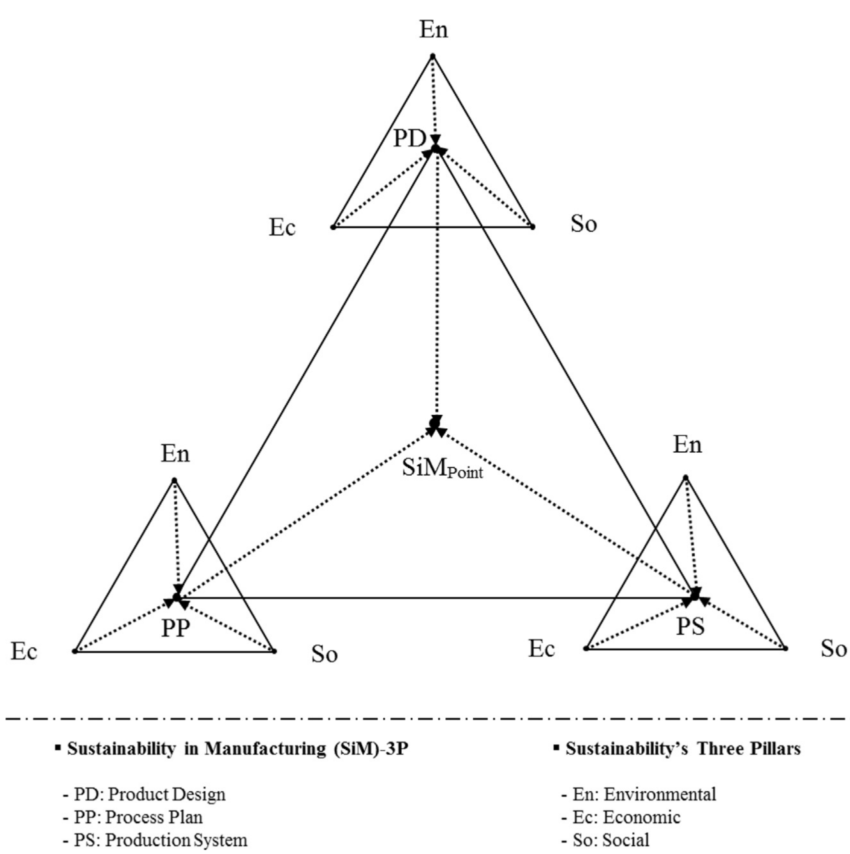

Fig. 3. Definition of SAiM based on the SiM-3P and three pillars of sustainability.

Table 1
Various sustainability impacts explained with the SiM-3P and three pillars of sustainability.

SiM-3P	Three pillars				
	En	Ec	So	Total	
PD	PD_{En}	PD_{Ec}	PD_{So}	PD_{SiM}	SiM_{Point}
PP	PP_{En}	PP_{Ec}	PP_{So}	PP_{SiM}	
PS	PS_{En}	PS_{Ec}	PS_{So}	PS_{SiM}	
Total	En_{Total}	Ec_{Total}	So_{Total}		

$$PS_{SiM} = F_3(W_{PSEn}{*}PS_{En}, W_{PSEc}{*}PS_{Ec}, W_{PSSo}{*}PS_{So}) \quad (4)$$

If the metrics can be converted and normalized to a single metric with the same units (e.g., cost), then the functions can be written as a weighted linear combination of the corresponding individual values as shown below.

$$SiM_{Point} = W_{PD}{*}PD_{SiM} + W_{PP}{*}PP_{SiM} + W_{PS}{*}PS_{SiM} \quad (5)$$

$$PD_{SiM} = W_{PDEn}{*}PD_{En} + W_{PDEc}{*}PD_{Ec} + W_{PDSo}{*}PD_{So} \quad (6)$$

$$PP_{SiM} = W_{PPEn}{*}PP_{En} + W_{PPEc}{*}PP_{Ec} + W_{PPSo}{*}PP_{So} \quad (7)$$

$$PS_{SiM} = W_{PSEn}{*}PS_{En} + W_{PSEc}{*}PS_{Ec} + W_{PSSo}{*}PS_{So} \quad (8)$$

Calculating the total row values (En_{Total}, Ec_{Total}, and So_{Total}) can be done in the same way if the values in each column have the same metric. They, therefore, can be calculated using a weighted linear combination of the corresponding individual values as shown below.

$$En_{Total} = W_{EnPD}{*}PD_{En} + W_{EnPP}{*}PP_{En} + W_{EnPS}{*}PS_{En} \quad (9)$$

$$Ec_{Total} = W_{EcPD}{*}PD_{Ec} + W_{EcPP}{*}PP_{Ec} + W_{EcPS}{*}PS_{Ec} \quad (10)$$

$$So_{Total} = W_{SoPD}{*}PD_{So} + W_{SoPP}{*}PP_{So} + W_{SoPS}{*}PS_{So} \quad (11)$$

Note, as before, there is no simple formula for computing SiM_{Point} using PD_{SiM}, PP_{SiM}, and PS_{SiM}.

4. Classification scheme for the inventory

A classification scheme is required to establish the fundamental structure of the research inventory of papers associated with the SAiM methods. The scheme is developed based on the SAiM definition in Section 3. This section presents the classification scheme and its associated notation. The proposed classification scheme is demonstrated using three published papers.

4.1. Proposed classification scheme

Fig. 4 shows the 5-level, proposed classification scheme. Level 0 is the top level. At this level, the SAiM definition is used to determine whether or not a paper is eligible to be included in the inventory. Levels 1, 2, and 3 set criteria for a generic classification scheme. Level 4 identifies the values of categorical variables specialized from the generic criteria for the SAiM methods. This scheme is meant to provide a list of potential keywords, in a prescribed order, that can be used to classify papers for retrieval.

4.1.1. Level 1, Level 2, and Level 3

Level 1 contains three criteria: *Content*, *Method*, and *Result*. *Content* includes *Scope* and *Object*. *Scope* is the boundary covered or targeted by the paper and has two sub-criteria: *Product Life Cycle (PLC)* and *Organizational Unit (OU)*. *PLC* identifies the product-life-cycle stage and *OU* identifies the organizational unit level the paper addresses. Even though *PLC* and *OU* have some similarities (Fransson, 2012), we distinguish them as follows. *PLC* is viewed from a perspective that focuses on a product and the activities to produce it. *OU* is viewed from a perspective of the enterprise that executes those activities. *Object*, the other sub-criterion of *Content*, identifies the sustainability areas assessed by the paper. *Object* has two sub-criteria: *Three Pillars of Sustainability (TPS)* and *Sustainability in Manufacturing Components (SiMC)*. *TPS* is essential for

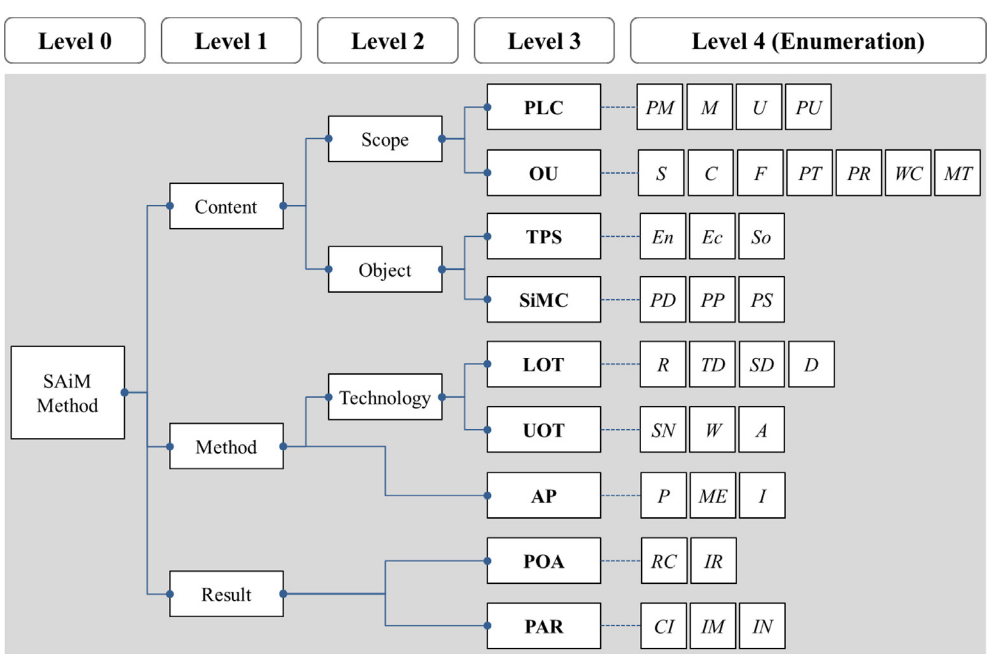

Fig. 4. 5-level classification scheme for the SAiM methods.

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assessing sustainability in manufacturing as specified in the proposed SAiM definition. *SiMC* refers to the SiM-3P, which is proposed as components of the SiM definition.

Method is associated with the actual assessment method(s) described in the research paper. *Method* has two sub-criteria: *Technology* and *Assessment Process (AP)*. *Technology* has two sub-criteria: *Level Of Technology (LOT)* and *Use Of Technology (UOT)*. *LOT* indicates the maturity level of the paper's particular method in terms of technology and *UOT* provides information about the type of technology used for the assessment. *AP* is related to the business process used to assess sustainability in manufacturing.

Result has two sub-criteria: *Purpose Of Assessment (POA)* and *Presentation of Assessment Result (PAR)*. *POA* and *PAR* identify the purpose and the desired result type of the SAiM method respectively.

4.1.2. Level 4

All of the sub-criteria described above combine to form Level 3 in the classification scheme. These sub-criteria can be treated as categorical variables, which are referred to as enumerations at Level 4. Each categorical variable may represent a value from a set of possible values that are determined based on consensus or common understanding. In this paper, values of the categorical variables are assigned based on the proposed SAiM definition and a comprehensive study of the SAiM methods.

The values of the categorical variable, *PLC* correspond to the various stages of the life cycle. They are *Pre-Manufacturing (PM)*, *Manufacturing (M)*, *Use (U)*, and *Post-Use (PU)* (Jaafar et al., 2007). *PM* usually represents the raw material extraction and processing stages. *PU* is mainly related to the disposal stage. The values of *OU* are *Supply chain (S)*, *Company (C)*, *Factory (F)*, *ProducT (PT)*, *PRocess (PR)*, *Work Cell (WC)*, and *Machine Tool (MT)* (Reich-Weiser et al., 2008; Feng et al., 2010). *TPS* and *SiMC* in the *Object* criterion refer to the proposed SAiM definition. *TPS* values are *Environmental (En)*, *Economic (Ec)*, and *Social (So)*, and *SiMC* values are *Product Design (PD)*, *Process Plan (PP)*, and *Production System (PS)*.

The values of *LOT* are *Research (R)*, *Technology Development (TD)*, *System Development (SD)*, and *Deployment (D)*. *R* indicates that the technology used is early in its development. *TD* indicates that the technology has been demonstrated, at least in a laboratory setting. *SD* indicates that the technology is ready to implement and test in a real factory. *D* indicates that the technology is in its final form and is ready to deploy. The actual value of LOT is based on the U.S. Department of Defense's Technology Readiness Levels (TRL), which is commonly used to assess the maturity of evolving technologies (US DoD, 2011). The values of *UOT* are *Scaling/Normalization (SN)*, *Weighting (W)*, and *Aggregation (A)* (Singh et al., 2012). *SN* is a way to put all measures on equal footing and make them dimensionless when sustainability indicators have different units and dimensions. *W* assigns weights to indicators as a way of indicating their relative importance. *A* is a means to calculate a composite (single) index from multiple indicators (Rao, 2008; Zhigang et al., 2012). The *AP* values refer to the OECD Sustainable Manufacturing Toolkit, which defines 3 main steps: *Prepare (P)*, *MEasure (ME)*, and *Improve (I)* (OECD, 2011). *P* refers to the process of identifying the scope and objective of sustainability assessment, and collecting the required data. *ME* refers to the process of determining the values of sustainability indicators. *I* is the process of analyzing the measured results and taking actions to improve the sustainability performance.

The values of *POA* are *Reporting/Communication (RC)* and *Identifying/Ranking (IR)*. *RC* indicates that the results of an assessment or decision can be communicated and forwarded to another entity. For example, the Global Reporting Initiative provides a set of protocols for sustainability reporting (GRI, 2010–2011). *IR* indicates that the purpose of the assessment is for identifying or ranking the level of sustainability against a predetermined set of benchmarks (Baumann and Cowell, 1999; Kinderytė, 2008). The values of *PAR* are *Composite Index (CI)*, *IMpact (IM)*, and *INdicator (IN)* (Kinderytė, 2008). *IN* refers to sustainability indicators directly calculated by sustainability metrics while *IM* indicates that impacts are determined based on the sustainability indicator values. *CI* represents an aggregated single score of sustainability based on the values of various sustainability indicators or impacts.

4.2. Notation for the classification scheme

The proposed classification scheme provides a basis for storing and retrieving papers from the inventory. This section proposes a mathematical notation to express the classification information for that purpose. Assume that C_i is a finite set of criteria values in the classification scheme, where i is the name of each criterion in the scheme. For example, the set of criteria values for *Result* is represented by C_{Result}. The relationships among all sets can then be represented as equations from (12) to (19).

In general, a criterion at level N of the classification scheme can be expressed as a union of related criteria at the next lower level, level N+1. For example, C_{SAiM}, a criterion at Level 0, can be represented as a union of $C_{Content}$, C_{Method}, and C_{Result}, which exist at Level 1. Similarly, $C_{Content}$ is a union of C_{Scope} and C_{Object}, where C_{Scope} is a union of C_{PLC} and C_{OU} and C_{Object} is a union of C_{TPS} and C_{SiMC}. The remaining criteria can be expressed in the similar way. Each of the sets for *PLC, OU, TPS, SiMC, LOT, UOT, AP, POA,* and *PAR* at Level 3 can be represented by their corresponding enumeration values.

$$\begin{aligned} C_{SAiM} &= C_{Content} \cup C_{Method} \cup C_{Result} \\ &= \{c | c \in C_{Content} \vee C_{Method} \vee C_{Result}\} \end{aligned} \tag{12}$$

where $C_i \cap C_j = \emptyset \; \{i \neq j \wedge C_i,\ C_j \in \{C_{Content},\ C_{Method},\ C_{Result}\}\}$

$$C_{Content} = C_{Scope} \cup C_{Object} = \left\{c | c \in C_{Scope} \vee C_{Object}\right\} \tag{13}$$

where $C_i \cap C_j = \emptyset \; \{i \neq j \wedge C_i,\ C_j \in \{C_{Scope},\ C_{Object}\}\}$

$$C_{Scope} = C_{PLC} \cup C_{OU} = \{c | c \in C_{PLC} \vee C_{OU}\} \tag{14}$$

where $C_i \cap C_j = \emptyset \; \{i \neq j \wedge C_i,\ C_j \in \{C_{PLC},\ C_{OU}\}\}$

$$C_{Object} = C_{TPS} \cup C_{SiMC} = \{c | c \in C_{TPS} \vee C_{SiMC}\} \tag{15}$$

where $C_i \cap C_j = \emptyset \; \{i \neq j \wedge C_i,\ C_j \in \{C_{TPS},\ C_{SiMC}\}\}$

$$C_{Method} = C_{Techology} \cup C_{AP} = \left\{c | c \in C_{Techology} \vee C_{AP}\right\} \tag{16}$$

where $C_i \cap C_j = \emptyset \; \{i \neq j \wedge C_i,\ C_j \in \{C_{Techology},\ C_{AP}\}\}$

$$C_{Technology} = C_{LOT} \cup C_{UOT} = \{c | c \in C_{LOT} \vee C_{UOT}\} \tag{17}$$

where $C_i \cap C_j = \emptyset \; \{i \neq j \wedge C_i,\ C_j \in \{C_{LOT},\ C_{UOT}\}\}$

$$C_{Result} = C_{POA} \cup C_{PAR} = \{c | c \in C_{POA} \vee C_{PAR}\} \tag{18}$$

where $C_i \cap C_j = \emptyset \; \{i \neq j \wedge C_i,\ C_j \in \{C_{POA},\ C_{PAR}\}\}$

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$$C_{\mathrm{SAiM}} = \{\{\{C_{\mathrm{PLC}} \vee C_{\mathrm{OU}}\} \vee \{C_{\mathrm{TPS}} \vee C_{\mathrm{SiMC}}\}\} \\ \times \vee \{\{C_{\mathrm{LOT}} \vee C_{\mathrm{UOT}}\} \vee C_{\mathrm{AP}}\} \vee \{C_{\mathrm{POA}} \vee C_{\mathrm{PAR}}\}\} \quad (19)$$

where

$C_{\mathrm{PLC}} = \{\mathrm{PM, M, U, PU}\}$
$C_{\mathrm{OU}} = \{\mathrm{S, C, F, PT, PR, WC, MT}\}$
$C_{\mathrm{TPS}} = \{\mathrm{En, Ec, So}\}$
$C_{\mathrm{SiMC}} = \{\mathrm{PD, PP, PS}\}$
$C_{\mathrm{LOT}} = \{\mathrm{R, TD, SD, D}\}$
$C_{\mathrm{UOT}} = \{\mathrm{SN, W, A}\}$
$C_{\mathrm{AP}} = \{\mathrm{P, ME, I}\}$
$C_{\mathrm{POA}} = \{\mathrm{RC, IR}\}$
$C_{\mathrm{PAR}} = \{\mathrm{CI, IM, IN}\}$

4.3. Demonstration of the proposed classification scheme

This section demonstrates how the proposed classification scheme and its notation can be used by applying them to three reference papers.

4.3.1. Analysis of reference papers

We analyzed three reference papers on the SAiM methods to demonstrate the implementation of the research inventory based on the proposed framework.

4.3.1.1. Paper 1: OECD sustainable manufacturing toolkit (OECD, 2011). This paper provides a set of internationally applicable, common, and comparable indicators to measure the environmental performance of manufacturing facilities of any size, in any sector, or in any country. The instance values of the criteria in the proposed classification are explained as follows.

- ***PLC.*** The OECD toolkit addresses the manufacturing (*M*) and use (*U*) stages of the product life cycle. The toolkit mainly focuses on the manufacturing stage, but it also considers energy consumption and greenhouse gas emissions from the use of the manufactured products. Therefore, C_{PLC} of the OECD toolkit is represented as {M, U}.
- ***OU.*** The indicators in the toolkit have been developed for the production activities of a single facility. That is, the OECD toolkit covers from work cell (*WC*), through process (*PR*) and product (*PT*), to factory (*F*) levels. The toolkit additionally explains that its coverage can be extended to include company (*C*) and supply chains (*S*). However, the OECD indicators do not cover detailed sustainability data at the machine tool (*MT*) level. Thus, C_{OU} is represented as {S, C, F, PT, PR, WC}.
- ***TPS.*** Since the toolkit considers only the environmental aspect (*En*) of sustainability, C_{TPS} of the OECD toolkit is represented as {En}.
- ***SiMC.*** The toolkit can be used to assess production system (*PS*), product design (*PD*), and process plan (*PP*). Therefore, C_{SiMC} is represented as {PD, PP, PS}.
- ***LOT.*** The technical level of the OECD toolkit is deployment (*D*). This level was chosen since the toolkit was internationally published by OECD and supports a guide document and web portal. Thus, C_{LOT} of the OECD toolkit is represented as {D}.
- ***UOT.*** The toolkit explains how to measure and scale/normalize (*SN*) its indicators and what data is needed for those computations. Thus, C_{UOT} is represented as {SN}.
- ***AP.*** The OECD toolkit presents 7 process steps, which align prepare (*P*), measure (*ME*), and improve (*I*). The guide provides detailed explanations about each of these steps. Thus, C_{AP} of the OECD toolkit is represented as {P, ME, I}.
- ***POA.*** The indicators addressed in the toolkit mainly assist internal management including reporting/communication (*RC*). In addition, it is possible to compare or rank (*IR*) the targets using a normalization factor. Thus, C_{POA} is represented as {RC, IR}.
- ***PAR.*** The OECD toolkit includes a number of indicators (*IN*), which are computed separately. The guide describes how to analyze costs and benefits in terms of improvement, but does not provide a composite index (*CI*) or values for impacts (*IM*). Thus, C_{PAR} is represented as {IN}.

4.3.1.2. Paper 2: a streamlined LCA framework to support early decision making in vehicle development (Arena et al., 2013). The paper proposes a life cycle performance measurement model that evaluates the environmental impacts of vehicles and captures the impacts of different technologies (e.g., plug-in electric vehicles or new materials) over the entire vehicle's life cycle. The model supports the early decision stages of assessing new vehicle technologies. The instance values of the criteria in the proposed classification are explained as follows.

- ***PLC.*** The product life cycle stages supported by the proposed model include raw material extraction (*PM*), material production (*PM*), product manufacture (*M*), product use (*U*), end of life (*PU*), and transportation. Thus, C_{PLC} of the paper is represented as {PM, M, U, PU}.
- ***OU.*** The model can assess the environmental performance of vehicles (*PT*) or their technologies. Two main operations (*PR*), painting and assembly, are specifically addressed in the paper. Thus, C_{OU} is represented as {PT, PR}.
- ***TPS.*** Since the assessments cover only environmental impacts, C_{TPS} is represented as {En}.
- ***SiMC.*** The paper assesses the environmental impacts over the entire life cycle based on fifty indicators that cover the SiM-3P. Therefore, C_{SiMC} is represented as {PD, PP, PS}.
- ***LOT.*** The paper provides a framework (*R*) that supports early decision making in vehicle development. That framework was evaluated by a multidisciplinary panel of eight experts. But, at the time of its writing, no empirical testing had been completed. Thus, C_{LOT} is represented as {R}.
- ***UOT.*** The model focuses on assessing major life cycle environmental impacts that are presented with quantitative data and qualitative data in vehicle characteristics and infrastructure dimensions. However, the paper does not employ techniques for normalization (*SN*), weighting (*W*), or aggregation (*A*). Thus, C_{UOT} is represented as an empty set, {}.
- ***AP.*** The paper identifies the life-cycle stages for which the performance measurement model applies and the relevant environmental indicators for each of those stages (*P*). It also calculates a set of indicators (*ME*). The paper argues that its model can be used to evaluate the strengths and weaknesses of alternative designs or technologies and hence can lead to improve vehicle design (*I*). Thus, C_{AP} of the paper is represented as {P, ME, I}.
- ***POA.*** The model can provide information on each specified indicator including its relative importance and direction (i.e., positive or negative) of the environmental impact (*RC*). Therefore, C_{POA} is represented as {RC}.
- ***PAR.*** The paper identifies fifty indicators (*IN*) and the relevance of each indicator's environmental impact (*IM*), but no composite index (*CI*) is introduced. Thus, C_{PAR} is represented as {IM, IN}.

4.3.1.3. Paper 3: sustainability assessment of U.S. manufacturing sectors: an economic input output-based frontier approach (Egilmez et al., 2013). The paper proposes a hierarchical assessment approach that consists of Economic Input-Output Life Cycle Assessment (EIO-LCA) and Data Envelopment Analysis models to assess environmental impacts and eco-efficiency of manufacturing sectors in the U.S. The eco-efficiency results of manufacturing sectors are based on environmental and economic performances simultaneously. The instance values of the criteria in the proposed classification are explained as follows.

- ***PLC.*** The paper analyzes the environmental impacts of fifty-three U.S. manufacturing sectors for the early stages of the life cycle (*PM*, *M*). It does not consider the environmental impacts of manufactured products either in use (*U*) or at the end-of-life phases (*PU*). Therefore, C_{PLC} is represented as {PM, M}.
- ***OU.*** The paper assesses the eco-efficiency of U.S. manufacturing sectors (*C, F*). It also assesses environmental impacts of some major manufacturing sectors in the supply chain (*S*). Thus, C_{OU} is represented as {S, C, F}.
- ***TPS.*** The eco-efficiency results indicate how industrial sectors affect the environment (*En*) while providing economic benefits (*Ec*). Thus, C_{TPS} is represented as {En, Ec}.
- ***SiMC.*** The approach is used to determine the indicators/environmental impacts of nation's manufacturing sectors in terms of products (*PD*) including textiles, pharmaceutical and medicine, apparel, and tobacco. Therefore, C_{SiMC} is represented as {PD}.
- ***LOT.*** Since the approach is at its research stage (*R*), C_{LOT} of the paper is, therefore, represented as {R}.
- ***UOT.*** The approach scales/normalizes (*SN*) the data obtained from the EIO-LCA model and aggregates (*A*) different environmental pressures into a single efficiency score without using subjective weighting (*W*). Thus, C_{UOT} is represented as {SN, A}.
- ***AP.*** The approach quantifies the eco-efficiency of each sector (*ME*). It uses those results to (1) benchmark the eco-efficiency of the sectors, (2) suggest improvements for eco-efficiency such as reducing energy usage and improving energy efficiency, and (3) make policy recommendations (*I*). Thus, C_{AP} is represented as {ME, I}.
- ***POA.*** The approach can determine eco-efficiency scores. These scores support reporting and communicating (*RC*), ranking (*IR*), and policy analysis. Therefore, C_{POA} is represented as {RC, IR}.
- ***PAR.*** The paper identifies the average sensitivity impact analysis (*IM*) of each of five environmental impact categories (*IN*) on the eco-efficiency of different manufacturing sectors. Examples of the impact categories are greenhouse gas (GHG) emissions, energy use, water withdrawals, hazardous waste generation, and toxic releases. An eco-efficiency value (*CI*) is determined through normalization and aggregation. Thus, C_{PAR} is represented as {CI, IM, IN}.

4.3.2. Implementation of research inventory

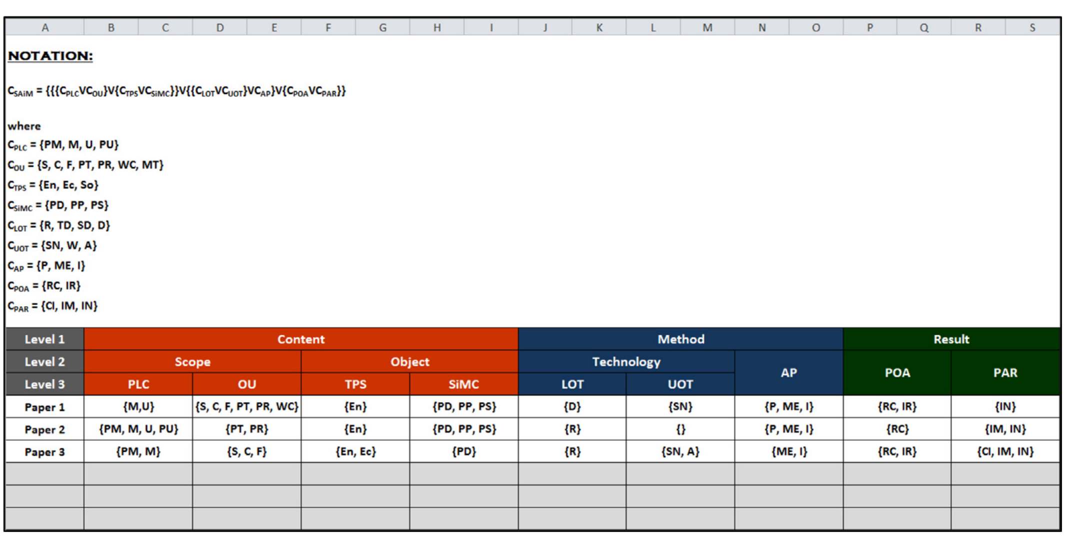
A prototype of the research inventory and its search engine was implemented to demonstrate the framework proposed in this paper. The prototype inventory contained three reference papers described in Section 4.3.1. Meta-information of those papers was expressed using our classification scheme, as shown in Fig. 5.

Fig. 6 shows the interface of a search engine for the prototype research inventory. The search engine was designed to include the capabilities of (1) identifying user requirements and (2) searching papers in accordance with those requirements. The criteria of the classification scheme were implemented as conditions for searching for the papers that the user wants. After the conditions were selected, this search engine started to find papers that had meta-information matched with the selected conditions. The conditions selected in Fig. 6 were manufacturing (*M*) in *PLC*, factory (*F*) in *OU*, environmental (*En*) in *TPS*, product design (*PD*) in *SiMC*, research (*R*) in *LOT*, aggregation (*A*) in *UOT*, measure (*ME*) in *AP*, identifying/ranking (*IR*) in *POA*, and composite index (*CI*) in *PAR*. The search engine found one paper, which satisfied all selected conditions, from the papers implemented in the prototype inventory.

4.4. Analysis and discussion

In the previous sections, we showed how to apply our framework to create and use a research inventory for papers on the SAiM methods. Three reference papers were analyzed and implemented in the prototype inventory. The prototype inventory was capable to represent key meta-information of those papers with the scheme proposed for classifying the SAiM methods. Such capability allows the search engine to identify the most suitable paper(s) for the selected conditions.

The proposed framework and research inventory have several advantages. First, the inventory enables papers to be more easily accessible and more widely available. Second, the inventory makes it easier to identify research gaps and aid in the creation of a research roadmap. Third, the classification scheme provides a basic understanding of the content of the papers in the inventory and



NOTATION:

$C_{SAiM} = \{\{\{C_{PLC} V C_{OU}\} V \{C_{TPS} V C_{SiMC}\}\} V \{\{C_{LOT} V C_{UOT}\} V C_{AP}\} V \{C_{POA} V C_{PAR}\}\}$

where
C_{PLC} = {PM, M, U, PU}
C_{OU} = {S, C, F, PT, PR, WC, MT}
C_{TPS} = {En, Ec, So}
C_{SiMC} = {PD, PP, PS}
C_{LOT} = {R, TD, SD, D}
C_{UOT} = {SN, W, A}
C_{AP} = {P, ME, I}
C_{POA} = {RC, IR}
C_{PAR} = {CI, IM, IN}

Level 1	Content				Method			Result	
Level 2	Scope		Object		Technology		AP	POA	PAR
Level 3	PLC	OU	TPS	SiMC	LOT	UOT			
Paper 1	{M,U}	{S, C, F, PT, PR, WC}	{En}	{PD, PP, PS}	{D}	{SN}	{P, ME, I}	{RC, IR}	{IN}
Paper 2	{PM, M, U, PU}	{PT, PR}	{En}	{PD, PP, PS}	{R}	{}	{P, ME, I}	{RC}	{IM, IN}
Paper 3	{PM, M}	{S, C, F}	{En, Ec}	{PD}	{R}	{SN, A}	{ME, I}	{RC, IR}	{CI, IM, IN}

Fig. 5. Implementation of three reference papers in the research inventory.

Please cite this article in press as: Lee, J.Y., Lee, Y.T., A framework for a research inventory of sustainability assessment in manufacturing, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.05.004

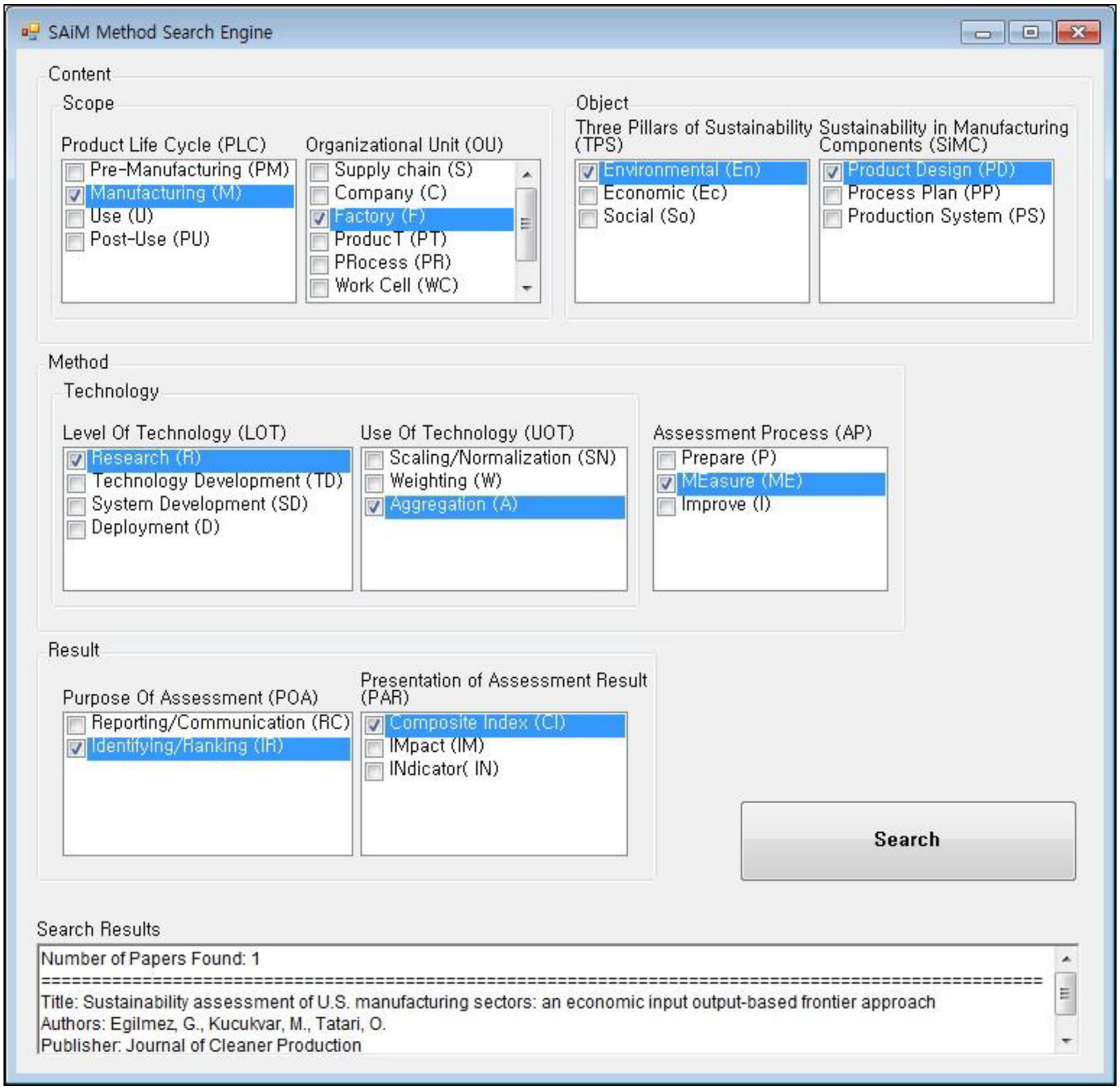


Fig. 6. Interface of a search engine for the prototype of the research inventory.

facilitates an examination of the state of the art in the topic area covered by the papers.

The demonstration reveals some issues for further research to improve the proposed framework and its implementation. First, if the research inventory provides a function to measure the level of suitability or similarity of papers to the users' conditions, the users can get more appropriate results from the inventory. It is also possible to measure similarity between papers given some concepts. Second, the proposed research inventory is for papers that address methods relevant to sustainability assessment in manufacturing. If the inventory can provide information on an actual industry for which the methods of the papers have been used or could be used, it would increase the ability of users to search for and use the papers most applicable to their interests. Lastly, a dictionary function would be useful since there could be confusion about some of the terms used in the research inventory. The dictionary could define the terms and concepts associated with classification scheme, and possibly antonyms and synonyms of some terms.

5. Conclusions and future research

This paper proposed a framework for a research inventory containing papers related to methods to assess sustainability in manufacturing. The framework primarily consists of two parts: an operational definition and a scheme to classify related papers. The SAiM definition is used to determine relevancy of any given paper to the topic of the inventory. This definition provides a basic idea of measurement science for sustainable manufacturing by identifying what factors should be considered for sustainability in manufacturing and how those factors can be assessed. The classification scheme provides key meta-information of the papers that focus on sustainability in manufacturing and its assessment. This scheme enables the research inventory to provide a means to search for the most relevant papers in an easier and more practical way.

The framework resulted from our study provides a systematic management of research papers and their applicability in an effective and efficient manner. The proposed concept could significantly improve search algorithms for scientific journals, which currently use traditional indexing schemes (e.g., a title and authors) or keywords. Users can be guided by meta-information of the SAiM methods to easily identify what they need and how to find their needs. The study could also enable manufacturing industries to improve the sustainability of their manufacturing processes by leveraging appropriate SAiM methods provided by the research inventory and hence to accomplish the goal of sustainable manufacturing.

A prototype of the research inventory and its search engine was demonstrated with three sample papers. That demonstration revealed some potential topics for further research. First, a similarity metric and a computational tool to compute it could improve the search capability. Second, a new classifier to indicate specific relevant industry sectors would increase the ability of users to search for and use the papers most applicable to their interests. Lastly, a dictionary and thesaurus functions would be useful since there could be confusion about some of the terms used in classification scheme. The dictionary could be implemented in some ontology language and the thesaurus could be implemented as a collection of mapping tools.

References

Adanza, E.G., 1995. Research Methods: Principles and Applications. Rex Book Store, Inc., Manila.

Allwood, J., 2005. What is Sustainable Manufacturing? Sustainable Manufacturing Seminar Series. Institute of Manufacturing, University of Cambridge. Available online at. http://www.ifm.eng.cam.ac.uk/ (accessed 21.11.13.).

Arena, M., Azzone, G., Conte, A., 2013. A streamlined LCA framework to support early decision making in vehicle development. J. Clean. Prod. 41, 105–113.

Baumann, H., Cowell, S.J., 1999. An evaluative framework for conceptual and analytical approaches used in environmental management. Greener Manag. Int. J. Corp. Environ. Strategy Pract. 26, 109–122.

Baumgartner, R.J., 2011. Critical perspectives of sustainable development research and practice. J. Clean. Prod. 19 (8), 783–786.

Brindle, R., Pack, L., 2011. ASME Sustainable Products and Processes Strategic Plan. American Society of Mechanical Engineers (ASME), Nexight Group. Available online at. https://community.asme.org/center_for_research_and_technology_development/m/default.aspx (accessed 10.11.13.).

Buselich, K., 2004. An Outline of Current Thinking on Sustainability Assessment – a Background Paper Prepared for the Western Australian State Sustainability Assessment. Murdoch University, Western Australia.

Devuyst, D., Hens, N., 2001. How Green Is the City? Sustainability Assessment and the Management of Urban Environments. Columbia University Press, New York, USA.

Do, N.C., 2010. The Definition of Sustainable Manufacturing. KEDM PLM. Available online at. http://fvortal.cimerr.net/plm/122?category=26 (accessed 11.12.13.).

Earth Charter Initiative, 2000. The Earth Charter. Available online at. http://www.earthcharterinaction.org/content/pages/Read-the-Charter.html (accessed 03.03.13.).

Ecologically Sustainable Development Steering Committee (ESDSC), 1992. National Strategy for Ecologically Sustainable Development. Available online at. http://www.environment.gov.au/resource/national-strategy-ecologically-sustainable-development (accessed 26.10.13).

Egilmez, G., Kucukvar, M., Tatari, O., 2013. Sustainability assessment of U.S. manufacturing sectors: an economic input output-based frontier approach. J. Clean. Prod. 53 (1), 91–102.

Ertas, A., Jones, J., 1996. The Engineering Design Process, second ed. John Wiley & Sons, Inc., New York, USA.

European Science Foundation (ESF), 2013. The MERIL Portal. Available online at. http://portal.meril.eu/converis-esf/publicweb/startpage (accessed 01.11.13.).

Feng, S.C., Joung, C.B., Li, G., 2010. Development overview of sustainable manufacturing metrics. In Proceedings of the 17th CIRP International Conference on Life Cycle Engineering, 6–12.

Finnveden, G., Moberg, A., 2005. Environmental systems analysis tools – an overview. J. Clean. Prod. 13 (12), 1165–1173.

Fransson, K., 2012. Chemical Risk Information in Product Chains: The Cases of Paint and Textile. Thesis for the Degree of Licentiate of Engineering. Chalmers University of Technology, Available online at. http://publications.lib.chalmers.se/records/fulltext/155896.pdf (accessed 13.06.13.).

Garetti, M., Taisch, M., 2012. Sustainable manufacturing: trends and research challenges. Prod. Plan. Control 23 (2–3), 83–104.

Glavic, P., Lukman, R., 2007. Review of sustainability terms and their definitions. J. Clean. Prod. 15 (18), 1875–1885.

Global Reporting Initiative (GRI), 2010-2011. Sustainability Reporting Guidelines, Version 3.1. Available online at. http://www.globalreporting.org (accessed 10.10.13.).

Gunasekaran, A., Spalanzani, A., 2012. Sustainability of manufacturing and services: Investigations for research and applications. Int. J. Prod. Econ. 140 (1), 35–47.

Hardcastle, A., Waterman-Hoey, S., 2010. Advanced Materials Manufacturing, Sustainability and Workforce development: Pilot Study. Washington State University Extension Energy Program. Available online at. http://www.energy.wsu.edu/ (accessed 28.07.13.).

Hasna, A.M., 2008. A review of sustainability assessment methods in engineering. Int. J. Environ. Cult. Econ. Soc. Sustain. 5 (1), 161–176.

Hediger, W., 2000. Sustainable development and social welfare. Ecol. Econ. 32 (3), 481–492.

Intelligent Manufacturing Systems (IMS), 2011. Maintenance for Sustainable Manufacturing (M4SM). White paper of the IMS M4SM MTP initiative. Available online at. http://www.ims.org/ (accessed 14.10.13.).

Jaafar, I.H., Venkatachalam, A., Joshi, K., Ungureanu, A.C., De Silva, N., Dillon Jr., O.W., Rouch, K.E., Jawahir, I.S., 2007. Product Design for Sustainability: a new Assessment Methodology and Case Studies. Environmentally Conscious Mechanical Design, John Wiley & Sons, Inc., NJ, USA, pp. 25–65.

Jayal, A.D., Badurdeen, F., Dillon, O.W., Jawahir, I.S., 2010. Sustainable manufacturing: modeling and optimization challenges at the product, process and system levels. CIRP J. Manuf. Sci. Technol. 2 (3), 144–152.

Jawahir, I.S., 2008. Beyond the 3R's: 6R concepts for next generation manufacturing: recent trends and case studies. In: Proceedings of Symposium on Sustainability and Product Development, IIT, IL, USA. Available online at. http://mmae.iit.edu/symposium/downloads/pres/Jawahir.pdf (accessed 23.02.13.).

Kamrani, A.K., Salheih, S.M., 2002. Product Design for Modularity, second ed. Kluwer Academic Publishers, Boston/Dordrecht/London.

Kinderytė, L., 2008. Analysis and comparison of methodologies for corporate sustainability assessment. Environ. Res. Eng. Manag. 4 (46), 66–75.

Koho, M., 2010. Production System Assessment and Improvement: a Tool for Make-to-order and Assemble to-order Companies. Tempere University of Technology (TUT), Publication 885. Doctoral dissertation.

Labuschagne, C., Brent, A.C., 2005. Sustainable project life cycle management: the need to integrate life cycles in the manufacturing sector. Int. J. Proj. Manag. 23 (2), 159–168.

Leahu-Aluas, S., 2009-2010. Sustainable Manufacturing: an Overview for Manufacturing Engineers. Sustainable Manufacturing Consulting. Available online at. http://sustainablemanufacturing.biz/ (accessed 13.01.14.).

Lowell Center for Sustainable Production (LCSP), 1998. What is Sustainable Production?. Available online at. http://www.sustainableproduction.org/abou.what.php (accessed 18.09.13.).

Lozano, R., 2008. Envisioning sustainability three-dimensionally. J. Clean. Prod. 16 (17), 1838–1846.

Manufacturing Skills Australia (MSA), 2008. Sustainable Manufacturing – Manufacturing for Sustainability. Available online at. http://www.mskills.com.au/info/sustainability/sustainability-brochures-and-reports (accessed 11.07.13.).

National Council for Advanced Manufacturing (NACFAM), 2009. Sustainable Manufacturing. Available online at. http://www.nacfam.org/Default.aspx (accessed 15.05.13.).

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60 (3), 498–508.

Organisation for Economic Co-operation and Development (OECD), 2009. Overview of the OECD Sustainable Manufacturing Toolkit Prototype. Available online at. http://www.oecd.org/industry/industryandglobalisation/44280332.pdf (accessed 01.12.13.).

Organisation for Economic Co-operation and Development (OECD), 2011. OECD Sustainable Manufacturing Toolkit. Available online at. http://www.oecd.org/innovation/green/toolkit/ (accessed 11.11.13.).

Pope, J., Annandale, D., Morrison-Saunders, A., 2004. Conceptualising sustainability assessment. Environ. Impact Assess. Rev. 24 (6), 595–616.

Poveda, C.A., Lipsett, M.G., 2011. A review of sustainability assessment and sustainability/environmental rating systems and credit weighting tools. J. Sustain. Dev. 4 (6), 36–55.

Prentice Hall Science Explorer, 2001. Inquiry Skills Activity Book. Prentice Hall, CA, USA.

Rao, R.V., 2008. Environmental impact assessment of manufacturing processes using a combinatorial mathematics based decision making method. Int. J. Sustain. Eng. 1 (1), 42–50.

Reich-Weiser, C., Vijayaraghavan, A., Dornfeld, D.A., 2008. Metrics for sustainable manufacturing. In: Proceedings of the 2008 International Manufacturing Science and Engineering Conference, IL, USA.

Rosen, M.A., Kishawy, H.A., 2012. Sustainable manufacturing and design: concepts, practices and needs. Sustainability 4 (2), 154–174.

Sevilla, C.G., Ochave, J.A., Punsalan, T.G., Regala, B.P., Uriarte, G.G., 1992. Research Methods. Rex Book Store, Inc., Manila.

Shoemaker, P.J., Tankard, J.W., Lasorsa, D.L., 2004. How to Build Social Science Theories. Sage Publications, Inc.

Sikdar, S.K., 2003. Sustainable development and sustainability metrics. Am. Inst. Chem. Eng. J. 49 (8), 1928–1932.

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2012. An overview of sustainability assessment methodologies. Ecol. Indic. 15 (1), 281–299.

University of California, Irvine (UCI), 2013. Sustainability Research Inventory. Available online at. http://www.sustainability.uci.edu/UCI_2013SustainabilityResearchInventory.pdf (accessed 13.01. 14.).

University of New Hampshire (UNH), 2010. UNH Sustainability Research Inventory. Available online at. http://www.sustainableunh.unh.edu/researchinventory (accessed 22.10.13.).

University of North Carolina (UNC) Institute for the Environment, 2010. Sustainable Research Inventory. Available online at. http://www.ie.unc.edu/index.cfm (accessed 12.01.13.).

U.S. Department of Commerce (US DOC), 2009. How does Commerce Define Sustainable Manufacturing?. Available online at. http://trade.gov/index.asp (accessed 27.07.13.).

U.S. Department of Defense (US DoD), 2011. Technology Readiness Assessment (TRA) Guidance. Available online at. http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf (accessed 25.10.13.).

Please cite this article in press as: Lee, J.Y., Lee, Y.T., A framework for a research inventory of sustainability assessment in manufacturing, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.05.004

U.S. Environmental Protection Agency (US EPA), 2003. Science Inventory. Available online at. http://cfpub.epa.gov/si/ (accessed 25.01.14.).
U.S. National Research Council (US NRC), Board on Sustainable Development, 1999. Our Common Journey: a Transition Toward Sustainability. National Academy Press, DC, USA.
Verheem, R., 2002. Recommendations for sustainability assessment in the Netherlands. In: Proceedings of the 22nd Annual Conference of the International Association for Impact Assessment.
Watt, J.H., van den Berg, S.A., 1995. Research Methods for Communication Science. Allyn and Bacon, MA, USA.
World Commission on Environment Development (WCED), 1987. Our Common Future – From one Earth to one World. Oxford University Press, Oxford, England.
Zhigang, J., Hua, Z., Sutherland, J.W., 2012. Development of an environmental performance assessment method for manufacturing process plans. Int. J. Adv. Manuf. Technol. 58 (5–8), 783–790.

Glossary

Acronyms

AP: Assessment Process
DOC: Department Of Commerce
DoD: Department of Defense
EIO-LCA: Economic Input-Output Life Cycle Assessment
EPA: Environmental Protection Agency
ESDSC: Ecologically Sustainable Development Steering Committee
ESF: European Science Foundation
3E: Equity, Environment/Earth, and Economy
GHG: GreenHouse Gas
GRI: Global Reporting Initiative
LCSP: Lowell Center for Sustainable Production
LOT: Level Of Technology
MERIL: Mapping of the European Research Infrastructure Landscape
MSA: Manufacturing Skills Australia
OECD: Organisation for Economic Co-operation and Development
OU: Organizational Unit
PAR: Presentation of Assessment Result
PLC: Product Life Cycle
POA: Purpose Of Assessment
3P: People, Planet, and Profit
SAiM: Sustainability Assessment in Manufacturing
SiM: Sustainability in Manufacturing
SiMC: Sustainability in Manufacturing Components
SiM-3P: Product design, Process plan, and Production system
TPS: Three Pillars of Sustainability
TRL: Technology Readiness Levels
TTSE: Two Tiered Sustainability Equilibria
UCI: University of California, Irvine
UNC: University of North Carolina
UNH: University of New Hampshire
UOT: Use Of Technology