Towards a shared understanding of sustainability information systems: A linked open data repository to integrate manufacturing sustainability indicator sets

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1. Introduction

Since the onset of the third industrial revolution, manufacturing has become more and more digitalized. As this transformation progresses, it also carries the potential to make manufacturing operations more sustainable. Since its conception, Industry 4.0 in Germany has therefore integrated the improvement of resource efficiency in manufacturing as a primary goal [1]. Given how numerous small and medium-sized enterprises (SMEs) are in the process of integrating Operation Technology (OT) and Information Technology (IT) in their operations, there seems to be a need to also advance the understanding of corporate sustainable management for manufacturing organizations. From a trans-disciplinary research perspective this new understanding can only be developed in collaboration with different stakeholders with an interest in the future of corporate sustainability management.

Evaluating the sustainability of manufacturing processes and products alone spans a wide area of on-going research. The sheer volume of data recorded and the processing of data and information on manufacturing and business processes is expected to enable workers to make better decisions whilst also being able to consider the sustainability impacts.

Environmental Management Information Systems (EMIS) have already been developed and are understood as Enterprise Information Systems (EIS) which "support users in operationalizing environmental goals, "consolidating and integrating information about the environmental impact into existing information systems" [2]. However, their one-dimensionality with regards to the concept of sustainability and their focus on supporting users in the creation of reports seem to limit their role in assisting enterprises to comply with regulatory standards. An information system with a holistic model of sustainability and a focus on daily applicability and support for internal-decision making is needed to support continuous sustainable development of an organization (cf. Feng et al, 2011). The conception phase of new sustainability information systems therefore offer an excellent opportunity to engage with workers and other stakeholders in this process. Their expert views will provide insights into which applications should be developed at all and which of those have a potentially high impact.

The wider goal of this research is therefore to engage sustainability managers and domain experts on environmental, social and economic sustainability in a co-creative dialogue towards a new conceptual model of sustainability information systems. To advance this dialogue collaboratively and systematically, a repository with guidelines for publishing re-usable conceptual models of sustainability research is missing. Ideally applied computer science and sustainability research communities could remedy this issue by collaborating on a platform for an open and trans-disciplinary model-driven design and

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development process. Minimizing resource consumption in the manufacturing sector, continuously developing quality work environments in factories of the future, as well as supporting SMEs to become more inter-connected with suppliers and customers around sustainability information are just three examples of major challenges in the future of corporate sustainability management. Being able to rapidly and continuously assess – in the some cases whilst also managing - all dimensions of the sustainability performance on different organizational levels requires an approach to software development which is designed to include a variety of stakeholder perspectives into the final product.

To advance the discussion along all aspects of this contribution at the workshop on the "future of environmental informatics research from the perspective of a young researcher" [3] the rest of the paper is structured as follows: Section 2 presents the research gap and challenges which have led to this investigation, Section 3 expands on the methodological approach chosen whilst Section 4 displays the work done and the first results of the investigation. Section 5 reflects on the preliminary results, as well as the future studies which may expand on these.

2. Related Works

The development of Sustainability Information Systems (SIS) is still at an early stage. SIS are herein not understood as sustainably designed software systems or software systems that are considered sustainable in their operation [4, 5]. Instead, they are seen as software systems that allow people in an organization to aggregate and manage sustainability information, relate the information to domain specific terms and analyze this information in relation to sustainability indicators and different organizational levels.

In research literature on sustainable manufacturing and assessment tools we regularly find organizational levels (cf. 6–11) referring to the levels of the so called "information pyramid of manufacturing" [12, p. 3]. Despite the emergence of several new reference architectures and models of industrial production processes over the last years, within manufacturing organizations the ISA-95 [13] standard still "represents the prevailing IT architecture in practice*"* [12, p. 3]. A consolidated set of terms used for these organizational levels in sustainability assessments and manufacturing organizations is needed for the co-creative development process.

The role of single indicator-based sustainability assessment tools in such a process is that these are built on indicator terms with exact definitions. These definitions allow researchers to qualitatively compare indicators from different indicator sets and synthesize them - wherever compatible - into one systemic model of inter-related terms.

Through a study of recent research literature on indicator-based sustainability assessments in manufacturing contexts, the following research gaps (*RGn*) were identified:

- *RG0*: No open source knowledge graph of indicator-based sustainability assessment terms exists to structure research and make indicator sets accessible and tangible for researchers and developers
- *RG1*: No open source conceptual models of corporate sustainability management exists to enable developers to e.g. start developing a domain model for a future sustainability information system

- *RG2*: General guidelines and quality criteria for the publication of complete and re-usable indicator sets for sustainability assessments [9, 14, 15] or ontologies for sustainability information systems are missing [16]
- *RG3*: For integrating sustainability assessment tools into daily practices, especially with regards to manufacturing and SMEs, performing accurate assessments in less time seems to be key (cf. [9, 14])
- *RG4*: Contributions to advancing the comparability of results from different indicator-based assessment tools are needed (e.g. [14])
- *RG5*: Systematization of the debate on lacking expressiveness of assessment results due to subjectivity and uncertainty are needed (e.g. [14])
- *RG6*: How to weight and aggregate performance data from machine and process level up to factory and systems level? [17]
- *RG7*: How to create a consolidated pool of reference values from empirical use-case studies across industrial sector? [9]
- *RG8*: Consolidation of indicator terms from different assessment tools based on their definitions and objective-function [7]
- *RG9*: Maintaining flexibility and adaptability to specific manufacturing contexts as a feature of a sustainable assessment tool and the comparability of their results across these contexts [9, 14]
- *RG10*: The integration of product and process oriented metrics for sustainability assessments still seems to be an unsolved challenge [7]

The focus of this ongoing investigation is to qualitatively address *RG8* by working out a practical contribution for *RG0* and to subsequently see what the results of an in-depth analysis of different indicator sets, their categorization and relation to organizational levels may be able to contribute to *RG1, RG4* and *RG6*. The idea other researchers seem to share is that solving *RG0* may enable a variety of advancements in *RG5, RG3, RG9* which can all be understood as beneficial for systematically advancing RG7 through supporting researchers and software vendors with consolidated terms. Furthermore, to launch the proposed indicator repository, a contribution to guidelines and quality criteria for publishing indicator sets needs to be made (*RG2*).

3. Methods

Since the proposed repository shall serve as the focal point for learning, discussing and exchanging about indicator-based sustainability assessment tools, its inception will include a mix of human-centered [18] and goal-driven design [19]. For the repository to succeed its purpose and target audience need to be well defined in form of at least two Personas collaborating through the repository. From these Personas and the repositories research focus, a set of qualitative criteria is derived which will act as the selection criteria for indicator-based sustainability assessments to be analyzed and integrated.

For the process of consolidation, each indicator-set must be analyzed qualitatively in-depth as well as undergo a technical transformation and categorization process. The overall analysis of each indicator-set must include (1) the extraction of all terms and their definitions into a machine readable data format, (2) the description of an objective-function or the scope of the indicator, (3) the assignment of all indicators

of the set to one or more organizational levels, as well as (4) grouping them to one of the topical clusters defined by the repository and finally (5) adding a reference to or including a detailed description of the process the methodology needed to perform the assessment in the designated way.

During this analysis the compatibility of each single indicator with all existing indicators from existing sets is to be checked qualitatively by assigning levels of conceptual compatibility. The threshold for a match of single indicators shall either be *Level 3* (Semantic) or *Level 4* (Pragmatic) compatibility [20].

Work report

Each in-depth analysis is to be accompanied by a scientific, subjective list-style work report. Its function is to allow the questioning and evolution of topical clusters and the assigned organizational levels within the repository. The work reports further document decisions made as part of the qualitative analysis and integration. The work reports enhance replicability and clarity of the qualitative analysis, as well as the decisions which were made throughout the process. Furthermore, the work report is a systematic approach to capture phenomena which may occur during a qualitative analysis and a document which relates these to one of the research gaps identified in Section 2.

More specifically: Any unintended side-contributions to the research gaps *RG1, RG4* and *RG6* which may occur during the analytical work on *RG8* should be captured systematically in this work report if the observation meets the following criteria: The analyst is able to specify either a type or describe the quality of the relation of the analytical phenomena to one of the abovementioned research gaps (*RGn*).

4. Preliminary Results

In the following section the basic concepts informing the design and the envisioned structure for a global research repository are outlined. As a result of the preliminary literature research on the concept of sustainable manufacturing and applicable sustainable assessment tools for manufacturing, four selection criteria for the repositories contents are presented and several indicator sets are proposed for further analysis. Part of the first results is a RDF based description of the core entities which constitute the initial version of the *ProMUT Indicator Repository Model.*

4.1 Repository Concept

The basic idea for the model repository for sustainability assessments is to start simple, to employ wide-spread best practice technology and be really easy and open from a workflow and governance perspective (RG0). A public *RDF* or *JSON-LD* based *git* repository is used as a publishing infrastructure for Linked Data (LD) [21]. The latter is one of the most widely used distributed version control systems and available for open research at no costs on Microsoft's *github.com* while the former are modern data formats for publishing linked data on the web [22].

Furthermore, qualitative and conceptual questions (*RG2*) seem to be even more important as the publication infrastructure for sharing and exchanging sustainable assessment and sustainable manufacturing models for research and development (cf. 23–25).

Additionally, an already developed taxonomy for topical categories (following the work of [26], [27], [15], [28] and [29]) can be tested against and developed along all indicators to be added to the repository.

The contents of the repository should match the following criteria as the aim is to have a transformative impact on the development of sustainability information systems which is applicable for SMEs in the manufacturing domain. Researchers and practitioners are encouraged to submit their indicator sets with a detailed work report through opening up an *Issue* and *Pull Request* on the repositories website[2][3]. The two personas interacting through the repositories shall be defined as the software engineer and the sustainability researcher though everyone is invited to propose indicator sets to be analyzed. At best the proposals meet the selection criteria for the repositories content and can be integrated under the principles of Fair Use or through the signing of a *Contributors License Agreement*. If the repository concept effort resonates within the applied sustainability research community a fitting governing body, a code of conduct for analysts, a repository manifest and an editing workflow needs to be detailed out.

4.2 Criteria for the selection of sustainable assessment tools (*Cn*)

For the repository to have the potential for a real transformative impact on manufacturing organizations, the investigation of sustainability assessments should be restricted to those which are regarded as applicable and useful in a manufacturing context from a SME perspective *(Criterion 1)* [9, 14]. Furthermore the assessment must address a holistic understanding of sustainability *(Criterion 2*). As a general criterion, indicator-based sustainability assessment tools shall only be included if they are published accessible, reusable and complete in some form (Criterion 3) to support the advancements of *RG0, RG1* and *RG2*.

- **C1:** Should be applicable for operations management in SME manufacturing contexts (or may be adapted to become so) and enable rapid assessment, highlight weak points and propose concrete actions & solutions [9, 14]
- **C2:** Should be based on a holistic understanding of sustainability and address the social, economic and environmental sustainability dimensions [9, 14]
- **C3:** Must be accessible and complete in some form of publication and come with an extensive definition of all its terms, their description, context and intended application (cf. 9)
- **C4:** Must relate to at least one of the following organizational reference frames (or therewith related terms): *Society, Enterprise, Factory, Cell, Machine, Product* and *Human [6, 7, 13]*

The Criteria **C2**, **C3** and **C4** are understood as general requirements and **C1** is seen as specific to the construction of a repository for the manufacturing domain.

[2] Being distributed under a prohibitive license might hinder indicator sets to be integrated into the *ProMUT Indicator Repository*.
[3] The *ProMUT Indicator Repository Website* is available at https://purl.org/promut/repository/

4.3 ProMUT Indicator Repository Model

For the initial version of the repository the model follows Ghahremanloo et al. in a generic and simplified design which is well suited for the very early stages of a collaborative repository in which "unseen sets of indicators need to be added to the ontology in an ad hoc fashion" [30, p. 79]. Furthermore the first versions of this model should be primarily designed to support human communication and only later versions shall be concerned with support for ontological data-integration tasks (cf. [31]).

The main classes proposed for the initial indicator repository model therefore are: *Indicator*, *Indicator Set, Indicator Category, Reference Frame* and *Sustainability Dimension (*see Figure 1*)*. An *Indicator* is made of an *Indicator Name, Indicator Description, Indicator Objective Function, Indicator Formula* and can be related to *Measurement Units* and a *Measurement Cycle*s. Furthermore each *Indicator* is assigned an *URI*, is part of one or more *Indicator Sets*, relates to one or more *Sustainability Dimensions* and organizational *Reference Frames*.

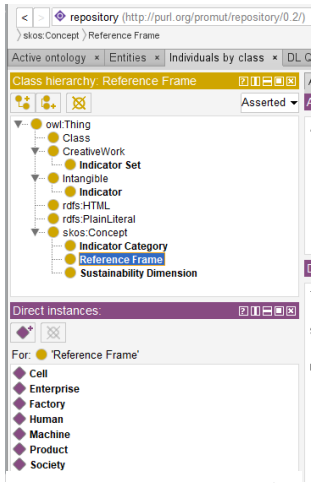

Fig. 1: Protégé Screenshot of the ProMUT Indicator Repository v0.2 Class Hierarchy and the Reference Frames.

The individual *Reference Frames* shall form the conceptual model of a manufacturing organization as embodied by the ISA-95 Standard [13], the Referenz Architektur Modell Industrie 4.0 (RAMI 4.0, [32]) and the works by Ahmad et al [11] and Huang and Badurdeen [6]: *Human, Product, Machine, Cell, Factory, Enterprise* and *Society*. The concept of an *Indicator Category* represents the categorization of an Indicator within a specific indicator set. The indicator categories shall support the identification of shared topical clusters of indicators within different sustainability assessment tools (cf. [26]). The RDF document describing this *ProMUT Indicator Repository Model* in more detail was made available for discussion and improvement and is the initial contribution to the repository. For specifying the relations between individual *Indicators* the *Simple Knowledge Organization System*[4] (SKOS) ontology is proposed.

4.4 First analysis of sustainability assessment tools

Chen et al [9] recommend the following indicator sets for assessing manufacturing performance on the level of factories: *Global Reporting Initiative* and *Dow Jones Sustainability Index*. An in-depth analysis of the GRI Standards was considered not feasible within the time constrains of this investigation.

Other indicator sets for assessments on the factory level which are extendable to match all abovementioned criteria are: *The ITT Flygt Sustainability Index, the Composite Sustainable Development Index*, and the *GM Metrics for Sustainable Manufacturing*. As the indicators from the *OECD Sustainable Manufacturing Indicators* [33] are accessible and complete in their definition *(C3*) it is the first indicator-set to be analyzed in depth.

[4] W3C Recommendation - Simple Knowledge Organization System https://www.w3.org/TR/skos-reference/

Following [14] assessment tools following *Gibson's Approach* [34] and the *Sustainable Value Stream Method* [35] match all four criteria. More literature research needs to be done to identify concrete indicator sets based on these two methods. Other indicator-sets identified as potential candidates for integration on the *Process*, *Machine* and *Product* levels are the *Unit-Manufacturing Process Model [36], the Unit Process Life-Cycle Inventory [37], ProdSi and ProcSi [6]*

Researchers and practitioners are encouraged to submit their complete indicator sets or proposals for further analysis through following the submission guidelines on the repositories website[5].

5. Discussion & Future Work

A first generic version of a repository model was proposed through (1) the definition of what an indicator is, (2) which types of links between indicators can be created, (3) the definition and selection criteria for indicator sets and (4) a draft of terms for organizational levels indicators and indicator sets relate to. The repository model allows researchers and developers to publish indicators and their definitions well-structured and as part of a global knowledge graph.

In the wider context of research & development it is expected that such a repository has several beneficial effects next to supporting the advancements of the identified research gaps: (1) documentation and accessibility of sustainability assessments (2) creating pragmatic guidelines for publishing, analyzing, integrating and comparing several of such models, (3) developing reference frames to structure the content of a repository (e.g. a topical and organizational reference frame), (4) defining criteria for future researchers on when to build on this repository for their research and (5) providing software engineers a starting point to explore machine readable, conceptual models of various scientific sustainability assessment tools applicable in real-life SME contexts.

This paper wants to highlight that it is possible for sustainability researchers to reach out to other research communities and engage with new stakeholders more easily when they start to think of their core concepts in linked open data. Contributing to the *ProMUT Indicator Repository* means to collaborate on re-usable research models and to design the future of applicable Sustainability Information Systems.

Future work

The proposed methodology must be validated through performing an in-depth analysis of several available indicator sets. After validating the methodology, the advanced indicator repository model should be consolidated, validated and released as stable.

In parallel, several authors of assessment tools or similar infrastructure efforts were already contacted and asked for a complete version of their work as an initial contribution to the repository. Additionally a set of supportive tools and documents for researchers to comply with the proposed methodology is to be developed so that the repository has the potential to be adopted by other researchers, grow, as well as be maintained. Finally, in a collaborative effort more and new indicator-based sustainability assessments studies could be identified and submitted to the repository for analysis and consolidation.

[5] The *ProMUT Indicator Repository Website* is available at https://purl.org/promut/repository/

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