sustainability

MDPI

Article

An Ontology-Based Knowledge Modelling for a Sustainability Assessment Domain

Agnieszka Konys

Faculty of Computer Science and Information Technology, West-Pomeranian University of Technology in Szczecin, ul. Żołnierska 49, 71-210 Szczecin, Poland; akonys@zut.edu.pl; Tel.: +48-91-449-56-62

Received: 24 November 2017; Accepted: 18 January 2018; Published: 24 January 2018

Abstract: Sustainability assessment has received more and more attention from researchers and it offers a large number of opportunities to measure and evaluate the level of its accomplishment. However, proper selection of a particular sustainability assessment approach, reflecting problem properties and the evaluator's preferences, is a complex and important issue. Due to an existing number of different approaches dedicated to assessing, supporting, or measuring the level of sustainability and their structure oriented on the particular domain usage, problems with accurate matching frequently occur. On the other hand, the efficiency of sustainability assessment depends on the available knowledge of the ongoing capabilities. Additionally, actual research trends confirm that knowledge engineering gives a method to handle domain knowledge practically and effectively. Unfortunately, literature studies confirm that there is a lack of knowledge systematization in the sustainability assessment domain, however. The practical application of knowledge-based mechanisms may cover this gap. In this paper, we provide formal, practical and technological guidance to a knowledge management-based approach to sustainability assessment. We propose ontology as a form of knowledge conceptualization and using knowledge engineering, we make gathered knowledge publicly available and reusable, especially in terms of interoperability of collected knowledge.

Keywords: sustainability; ontology; sustainability assessment; knowledge systematization; knowledge representation

---

1. Introduction

The term "sustainability" increasingly refers to an integration of social, environmental and economic responsibilities [1] to ensure prosperity, environmental protection and social cohesion [2]. Clearly, the goal of achieving sustainability has a multidisciplinary character and cannot be achieved only with the use of technology [3]. Further, supporting decision-making and policy in a broad environmental, economic and social context is conducted by sustainability assessment (SA), transcending a purely technical and scientific evaluation [3,4]. The aim is to pursue plans and activities that make a suitable contribution to sustainable development (SD) [5]. Research on sustainable development aims to improve our understanding of interactions between natural and social systems [6] and to guide these interactions toward more sustainable trajectories [7,8]. The concept of sustainable development has been an important focal point for decision-makers in business [9]. To advance sustainable development, obviously an adequate approach is needed. Notwithstanding the used approach, achieving effects should be measurable. According to [1,10] to ensure an appropriate level of sustainability new challenges are required by adapting an appropriate solution to a given decision situation. The existing number of the various approaches and their narrow areas of practical applicability [3,9], show that proper matching is not a trivial task and that the selection process is complex and difficult, however [8]. It should be pointed that appraising the selected approaches purveys the information of particular forms for measuring sustainability [11] and simultaneously emphasizes shortages of the existing approaches [3,9,10] and the lack of comprehensive knowledge systematization in this domain [12–14]. In this context, a multi-dimensional knowledge-based model of sustainability assessment approaches may cover this gap.

An analysis of the literature allows identifying a set of different approaches for sustainable measurement. Mostly, they consign three dimensions of sustainability: social, environmental and economic. They can be categorized to several groups, i.e., frameworks [1,8,15], indicators [12,16] and measures [11,14]. Due to a wide range of applications of the approaches for sustainability development, these solutions differentiate between each other [9,16], although some similarity in features exist [1]. Depending on which approaches are used, the results of impact assessments can vary considerably in either sustainability dimension. For example, frameworks provide the guidelines for a given domain of interest or considered problem in reference to the sustainability dimensions [17], while metrics and indicators are used to assess the sustainability performance of a process [12] or a system [11], to evaluate the process toward enhancing sustainability [7] and to assist decision-makers in evaluating alternatives [18].

The selection of a given approach depends on many factors [9]. A number of available solutions, distinguishing itself from each other, may cause essential problems with proper selection [1,14]. An analysis of literature shows a wide range of the domains and fields to which they are applied [19,20]. According to [21–23] there is a clear need to understand issues related to the compliance level and standards offered by the given approaches, including the monitoring processes and effects. Furthermore, the inconveniences related to the limitations of the analysed approaches, the offered level of reliability and their consistency and objectivity cannot be omitted [9]. Additional problems concern the partial [14], or dedicated, character of most of them [10,24].

Consequently, there is a lack of guidelines in how to select a particular approach and how to use it in a particular decision situation. Another inconvenience may concern a shortage of standardization, systematization and orderliness of terms for assessing particular form of sustainability [9,14,21]. It seems that this problem should considered the multi-dimensional issues. Thus, the crucial question is to find a reasonable approach and cut-off point between comprehensiveness and manageable multi-dimensional taxonomy. This issue highlights specific gaps in the research, at least from an empirical standpoint. It reflects not only the overall lack of a sustainability-based multi-dimensional taxonomy but also the restricted scope of most studies [9,11]. Therefore, there is a need for a knowledge base of comprehensive methods and tools to be developed for sustainability performance evaluation and communication [3,8,9,14]. That solution needs an inherent coherence so as to be able to link between available approaches with different levels towards sustainable development.

Based on the literature analysis, we can identify research gaps of knowledge systematization in the sustainability assessment domain. The aim of this research is to propose a knowledge-based model of sustainability assessment approaches. The authors answer the paper's research questions by conducting a large-scale (systematic) literature review and, subsequently, using conceptual theory, build a taxonomy, along with related research propositions. The in-depth analysis of miscellaneous types of approaches allows constructing a knowledge model in the form of a taxonomy and, afterwards, ontology. The aim is not only compartmentalizing particular forms of solutions of assessing sustainability but to ensure formal, practical and methodological guidelines of how to find the comprehensive knowledge of them.

Formally, the rest of the paper is organized as follows: Section 2 offers a concise literature review of approaches oriented on development and identifying actual challenges in the sustainability assessment domain. In Section 3, the knowledge systematization in the form of analysis available approaches is provided. It is a foundation to elaborating the authors' taxonomy. Thus, knowledge engineering conceptualization is yielded in the form of a taxonomy in the aftermath of the ontology. The concluding section provides the main outcomes of the paper and proposes some points for further discussion.

2. Literature Review

Over the years, there have been consistent efforts at local, regional, national and international levels to identify appropriate sustainability approaches as per the sustainability context and coverage [9]. Nowadays, maintaining an adequate level of sustainability is a crucial element for most businesses and organizations [25]. The meaning of this endeavour has increased significantly recent years. Consequently, it has a direct impact on a number of actions related to preserve sustainability [16,20]. Some global [1], international [19], national and regional [10] strategies include this important aspect towards sustainable development in terms of the objectives and targets defined in the strategy. Thus, the proper identification and actions development allow to achieve a continuous long-term improvement of sustainability [9] and the progress of these processes should be monitored continuously to ensure an adequate level of quality [19]. For this purpose, assessment using dedicated approaches for sustainability development may help in achieving success.

An analysis of the literature allows distinguishing various types of approaches for sustainability assessment. They refer to the three basic dimensions of sustainability especially including social [9], environmental [26] and economic [12] aspects, or other dimensions, such as ecological [27], cultural [1] and institutional [17]. As there are a number of available initiatives that exist with respect to indicators, measures and frameworks for sustainable development, the comprehensive, multi-dimensional overview of various sustainability assessment approaches should be provided. Each of the analysed groups has specified, distinguished features. These approaches are committed to assess [18], support [7,17], or measure [1] the level of sustainability. Moreover, the need for sustainable development have forced researchers to create comprehensive solutions consolidating the metrics [28], measures [9], frameworks [17,29] and indicators [12,17,30]. These selected groups of approaches are presented below in detail.

2.1. Frameworks

Frameworks are the most numerous group dedicated to assessing sustainable development. In most studies, frameworks are treated as basic tools to sustainability evaluation [3,9]. They offer guidelines in achieving sustainable development. Mostly, they concentrate on providing a methodological base for sustainability development [15], assisting the overall processes [12] and offering a holistic approach that identifies key relationships between three main dimensions of sustainability [26]. For measuring sustainability with a focus on integration of environmental, economic and social aspects [31] the frameworks enable evaluating the level of sustainability [32] by describing the progress along all three dimensions pointed out above. For example, Cuthil [33] explained a conceptual framework for social sustainability that includes two factors which describe an interdependent and self-reinforcing relationship between four key components: (1) social capital; (2) social infrastructure; (3) social justice and equity; and (4) engaged governance. Additionally, Spohn [34] explained the LCSP framework, which focuses primarily on the environmental, health and safety aspects of sustainable production. The United Nations Environment Programme (UNEP) launched the Global Reporting Initiative (GRI) in 1997 for improving the quality, structure and coverage of sustainability reporting [1,9]. Hofstede [35] introduced the cultural framework to compare cultures, by assigning scores for each of six dimensions. Furthermore, the necessity of an integrative framework from an interdisciplinary perspective promotes the authors [8] to elaborate a three-dimensional cube model of sustainable consumption behaviour (SCB-cube) extended by a fourth impact dimension. Additionally, the United Nations Commission on Sustainable Development (CSD) established a framework of monitoring the variety of sustainability indicators for evaluating the performance of government towards sustainable development goals [1]. The Wuppertal Institute devised an entrepreneurship-dedicated framework of sustainability by addressing the four dimensions of sustainable development, as defined by the United Nations CSD [12]. It contains indicators for the four dimensions of sustainable development together with interlinkage indicators between these dimensions [1].

2.2. Indicators

The frameworks contain series of indicators designed to determine the evaluation of sustainability. The analysis of the literature allows identifying a wide range of solutions significantly differing in praxis, focused on different domains, i.e., supply chain, purchasing [31], food, management [25], material use, industrial ecology [1], waste production disposal, toxics [36] and greenhouse gas emission [11]. Indicators are increasingly recognized as a useful tool for assessing and evaluating the performance [37] in fields such as environment, economy, society, or technological development [38]. They are often integrated in some way to give a means of measuring progress towards sustainability [12]. Mostly, they offer both information to decision-makers to formulate strategies and communicate the achievements to the stakeholders [39] and afford trends on improvement, as well as warning information on declining trends for the various dimensions of sustainability, i.e., economic, environmental and social aspects [34]. Sustainability indicators differ from traditional development indicators because of the interrelationships between natural and cultural resources and stakeholders [9,40,41]. On the basis of the available researches it is possible to point at various types of indicators, both for entrepreneurship [12] and for sustainable development [42,43]. Predominantly, the indicators cover some aspects of sustainability dimensions, providing specific functionalities (descriptive, performance, efficiency, sustainable reference values, production, regulatory, accounting, economic, quality and ecological indicators) referring to the three sustainability dimensions [12,25]. Furthermore, the indicators can also be divided into partial [16] and synthetic indicators [12]. Synthetic indicators have a more general character than partial ones. They describe and measure the whole processes constituting the quality of life of the population [25] and the total effect of mutual impact of the economic sphere [16] and the environment [18]. The synthetic indicators can contain, among others: The Sustainable Society Index (SSI) [32], the Environmental Performance Index (EPI) [44], the Index of Economic Well-being [45] and the Environmental Sustainability Index (ESI) [46].

2.3. Measures and Metrics

The level of sustainability can be also assessed using measures and metrics. The terms "metrics" and "indicators" are often used interchangeably [1]. They provide both quantitative and qualitative measures of sustainability. The main difference concerns the fact that a metric gives a quantitative characterization [9] or an index value, whereas indicators provide a narrative description in addition to the qualitative characterization [47] and may include one or more metrics [12]. Similar to frameworks and indicators, the process of measurement selected sustainability aspects is considered in terms of three groups of metrics corresponding to the three main aspects of sustainability: environmental metrics, economic metrics and sociological metrics [11]. Urgent and complex problems are challenging measures to adapt to a given situation in sustainability assessment domain. A growing amount of the measures are applied in different domains, i.e., purchasing, supply management, energy, pollutant dispersion and material utilization. The general aim of it is to provide a complete evaluation of the various aspects of businesses, processes and services. For example, the measures in relation to the main purchasing processes [14] may refer to the following issues: make or buy, supply market analysis [48], spend analysis [49,50], sourcing strategy [51,52], specs definition [53,54], supplier selection and contracting [52,55], supplier development [51,56], management of the order cycle [52], supplier involvement in NPD (new product development) [55,57], supplier integration in order fulfilment, supplier evaluation [52,53,56] and collaboration processes [58,59].

One of the previous significant studies on sustainability metrics, named AIChE and IChemE [43,60], considered the evaluation of alternatives. However, an analysis of literature allows to identify a large number of indicators that have been suggested for use in determining improvements made to chemical processes, a manufacturing site, or a manufacturing enterprise [43,60]. Generally, these metrics or indicators refer to different aspects (e.g., material utilization, energy use, water use, toxics dispersion, pollutant dispersion and greenhouse gas emission) [61,62]. These studies emphasized the opportunities for much discussion on sustainability and sustainability metrics [11].

Apart from single approaches, the more complex solutions including a set of indicators or measures exist. Additionally, an analysis of literature provides the information of indicator systems applied for sustainable dimensions [25]. Some examples of conventional sustainability performance indicators are shown in [63]. Additionally, existence of core indicators for sustainable development cannot be omitted [1]. Further, the sustainable development indicators (SDIs) are used to monitor the EU Sustainable Development Strategy (EU SDS) in a report published by Eurostat every two years [64]. They contain more than 100 indicators. The aim is to provide an overall picture of whether the European Union has achieved progress towards sustainable development in terms of the objectives and targets defined in the strategy [64].

2.4. Discussion

A number of existing approaches for measurement and assessment of the level of sustained development emphasizes its role but the main problem may concern the consistency and range of them. Some of them reflect to the entrepreneurship sustainability domain but a major part refers to selected sustainability dimensions. An analysis of the literature shows a wide range of domains and fields in which they are applied (e.g., the field of transport infrastructure [65], systems for public rental housing communities [66], SMEs [67], sustainability in purchasing and supply management [14,48–52,59], cultural factors of sustainable energy [35], sustainable consumption [8], societal progress and others. There are only exemplary domains and fields that should, in fact, be exclusively aimed at showing the diversity of applied applications. The refinement of appropriate methods may ensure the relevance of performance indicators and their reflection of different stakeholder perspectives, including vulnerable stakeholder groups [12]. Furthermore, the current indicator frameworks that are available to measure overall business sustainability do not effectively address all aspects of sustainability at an operational level [1].

Depending on which indicators, measures, or metrics are used, the results of impact assessments can vary considerably in either sustainability dimension [8]. Thus, an important challenge is weighing the relevance of different indicators measures or metrics for an overall balance [68]. Moreover, it seems that an integrative solution from an interdisciplinary perspective is needed. Furthermore, there is generally a need for research to adopt a wider view in terms of levels of analysis. However, we have to remember that, due to unique criteria or features, it is quite difficult to apply a given approach for a given decision situation.

When analysing particular approaches, it should be pointed that they typically do not reflect the focus throughout the field of sustainability. Furthermore, companies claim to address sustainability across different tiers but research has failed to develop appropriate approaches to verify whether this is truly the case [14]. According to Sikdar [11] no consensus existed on a reasonable taxonomy of metrics [9] and, similarly, for indicators and frameworks [3]. The need of finding ways of consolidating the approaches in one main aggregate solution might provide overall means of the progress towards sustainability, although such consolidation of the approaches is difficult. Moreover, the need for sustainable development has forced researchers to create comprehensive solutions consolidating both the metrics, measures, frameworks and indicators. In response to the above-mentioned shortcomings, domain knowledge should be collected.

2.5. Attempts to Knowledge Systematisation in the SA Domain

An increasing trend of promoting sustainability may be seized by applying knowledge-based approaches, especially including knowledge-based models and the elements of knowledge management [65]. Reviewing the literature and existing approaches, there were narrow attempts to adapt knowledge engineering mechanisms to enhance obtaining information of sustainability assessment solutions. Existing single knowledge-based approaches, like frameworks [65], knowledge management factors [24,69] and sets of gathered measures and taxonomies [14], emphasize both the taken activities and necessity of implementation of that type of solution [70]. For example, the importance and key issues of promoting sustainability through knowledge management were proposed by [65], introducing a conceptual framework for managing sustainability knowledge. An attempt to construct a taxonomy of sustainable purchasing and supply measures was elaborated by [14]. It synthesized selected measures of sustainability at different levels (dyadic, supply chain and network, with reference to social and environmental dimensions) and organized these into the taxonomy. The proposed solution should be treated as an empirical, rather than a normative, taxonomy [14], suggesting that the future development is needed. In a study by Wang [24], it was highlighted that knowledge management factors enabling green supply chain collaboration underlines the requirement of adapting knowledge engineering mechanisms in this field [24]. This refers to the consequent dimensions, like strategic, managerial, organizational, technological, environmental, financial, human-socio and operational ones. There is a need to conceptualize the construct of knowledge models more clearly, thereby facilitating future practitioners, researchers and funding bodies in developing a consistent body of knowledge [4]. Thus, the focus on knowledge management should not be missed.

In general, the scarcity of these studies highlights many opportunities for future development, despite the methodological challenges. The proper identification of the issues to elaborate compliance and standards for further taxonomy stresses the need to its application across the sustainability assessment domain [28]. Mostly, the end-users do not ask how to correctly use any of the analysed approaches, or how to involve other parties in selected activities, i.e., in setting specifications, managing the stakeholders, or evaluating suppliers [24]. Given the number of studies in sustainability assessment domain, the field of taxonomy elaboration appears relatively mature on the surface [71]. Reviewing the existing approaches and knowledge-based solutions reveals there is still a great deal of heterogeneity in their application [3]. Yet, there is even greater variability across levels of analysis, with a distinct lack of research on the taxonomy elaboration and further development. The analysed knowledge-based approaches have not adapted enough to sustainability assessment domain requirements. Analysing proposed attempts to deal with this problem concentrates only on the finite and restricted fields and sets of sustainability assessment approaches.

Many papers [9,11,14,72] claim that there is the need of a complex, multi-dimensional knowledge-based solution, whereas, in reality, the proposals only focus on specified issues [1,3] or selected groups [8,23]. Although there are various efforts on assessing sustainability, only few of them have an integral approach taking into account one set of solutions (i.e., metrics, indicators) focusing on environmental, economic and social aspects [9]. In most cases the focus is on one of the three aspects. Surprisingly, our review confirms a lack of knowledge systematization of the existing comprehensive taxonomy dedicated to various aspects of the sustainability assessment domain. Highlighting the gap of the overall lack of comprehensive knowledge-based approaches for promoting the sustainability assessment pathway offers new perspectives for knowledge engineering mechanism's development in the form of taxonomy and ontology.

3. Knowledge Model for Sustainability Assessment Domain

A well-defined construction of the knowledge base, especially in the form of an ontology, requires adapting a proper methodology. There is a wide range of research guidelines and frameworks to ontology construction, development and maintenance, i.e., Noy and McGuiness [73], Uschold and King's [74], Grüninger and Fox's [75], METHONTOLOGY [76] and On-To-Knowledge [77]. Generally, it is impossible to indicate the optimal method for ontology construction and development. Moreover, it is rather difficult to recommend a proper method to model a given domain. Indeed, it is achievable to find common assumptions for a proper ontology design and construction, regardless of selected methodology. Predominantly, most of the analysed methodologies based on competency questions to verify the coherence and correctness of constructed ontology. This validation process refers to activities of knowledge structuralization and checks the correctness of the implemented knowledge base.

The proposed ontology is developed with an operational perspective based on a literature review and a specified analysis of key factors of the sustainability assessment domain. A general procedure of an ontology construction is adapted from Noy and McGuiness [73] and it consists of the following phases: (1) defining a set of criteria; (2) taxonomy construction; (3) ontology construction; (4) formal description; (5) defined classes creation; (6) reasoning process; (7) consistency verification; and (8) a set of results. Each step requires specific activities. The first step in building the ontology is defining its domain and range. To perform this process deep domain analysis is required. This process allows remoulding the unstructured data, gathered from a wide range of scientific papers, into semi-structured form. Based on it, the set of criteria and sub-criteria is defined. This process is followed by extraction concepts, relations and the properties from the scattered sources to a taxonomy form. Expanding the taxonomy and implementing it using Ontology Web Language (OWL), provides a formal and structured method to gather, organize and share data from the sustainability assessment domain. To ensure a full formal description of the proposed ontology, the Description Logic (DL) standard is used. To understand whether the ontology is coherent, the defined classes are constructed. The reasoning process allows verifying the correctness both of the constructed defined classes and the whole ontology. Consequently, at the end of this, the set of results is provided (Figure 1).

Figure 1. A general procedure of an ontology construction.

Performing the deep domain analysis is the first step of the ontology construction process. It is conducted by selecting the set of sustainability assessment approaches (see Section 3.1). To determine the final set of properties and sub-properties, the class hierarchy is built. This is a general foundation for a taxonomy construction for the sustainability assessment domain (see Section 3.2). Further, the taxonomy is a backbone for the ontology construction as a next step (see Section 3.3).

Further, to validate the ontology, its consistency, quality and correctness was checked. This process was investigated using some validation queries (see Section 3.3.4). The applied case studies checked the practical choices of the considered areas of sustainability assessment. The obtained results service finds satisfaction from maintenance experts who validate the technical choices taken during the design process and, consequently, demonstrate the efficiency of the proposed ontology. These phases are precisely described in this section.

3.1. Domain Analysis

Dynamic development of the sustainability assessment domain offers new perspectives to impact assessment geared towards planning and decision-making on sustainable development [78]. These perspectives require discrimination and evaluation in a solid and reliable manner, whether new developments meet the needs of the present without compromising the ability of future generations to meet their own needs [79]. Performing a sustainability assessment involves integrating sustainability principles, thresholds and targets in the evaluation, as well as the available approaches and functionalities offered by them. Focusing on the sustainability assessment domain should aim at the impact on the development ensuring comprehensiveness and robustness of the evaluation supporting the decision-making process [10,24,61]. The complexity and the multidimensional facets of sustainable development are pushing to deep analysis of this domain to find new models and paradigms, leading to the new options of further development of this domain [7].

The main aim of sustainability assessment is both to ensure an optimal contribution to sustainable development and to pursue the understanding of the key issues regarding the existing approaches, their differences and dependencies [1,3,9,12]. This process was propped up by the extensive analysis of available approaches dedicated to this domain. As a result of the comprehensive literature studies, the analysis contains the set of measures, metrics, frameworks, factors, indicators and methods dedicated to the sustainability domain. They are characterized by different fields of application. The aim of the analysis is to identify attributes, criteria and indicate the various domains of its application, especially including: purchasing, supply management, resource usage, production and consumption, among others. Following the conceptual model of the domain analysis (see the supplementary material, conceptual_model.xls), the matrix intends to depict the general purpose of the comparison schema arrangement. Meaning the rows contain the set of properties and sub-properties, which is consistent for each group of analysed approaches, whereas the set of approaches is shown in the columns. These columns show the group of different types of sustainability assessment solutions, especially including measures and metrics, methods and tools, taxonomies, indicators and frameworks. The detailed description is provided in supplementary materials (see comparison_analysis.xls and taxonomy.xls).

Predominantly, apart from the domain and the field of application, these solutions distinguish between each other by the type of gathering data/knowledge, exploitation of other solutions and applicability. Mostly, the process of data gathering is based on surveys and questionnaires [12], expert knowledge [33] and literature review [14]. This process is restricted by data availability and contingency. Oftentimes, the offered sustainable approaches are developed or adapted on the basis of existing solutions [11,80]. Furthermore, it is worth mentioning the limitations of the analysed approaches, offering a level of reliability and their consistency and objectivity.

The deep literature analysis allows identifying sets of various approaches: measures, metrics, frameworks, factors, indicators and methods. Each set of approaches contains the established set of properties. The level of accuracy depends directly on the available and gathered information of a particular solution. The constructed set of properties is a final result of this analysis. The comparative analysis provides the set of 44 approaches. Elaborating the set of criteria requires a profound review of a wide range of papers. There are a number of principles to be taken into consideration in the comparative analysis: domain of usage, aim, type of gathering knowledge/data, exploitation of other solution, additional information, divisions/subcategories/levels/key components, types, dimensions, limitations, level of reliability/lack of the approach, dedicated group of users and challenges. Below, they are presented in detail.

- The leading domain of usage is shown in the majority of analysed approaches [1,3,9,14]. Often, the measures, frameworks and indicators are described and affixed by case studies [10,21] that serve as an indication to establish the fields of application. Moreover, possible areas of usage are also provided [49,62]. To provide a basic knowledge of approach destiny may help the end-users or business entities with the selection of a particular form of the solution. Various existing domains distinguish the practical application of analysed approaches. Commonly, they cover purchasing [49], production [81], supply management [14,82], or different forms of resources usage [11,43,83]. There are few solutions without identification a specified domain [12,27,80]. Continuously, new areas are added depending on market demands. The remaining domains refer to the tourism sector [40], SMEs sector [84] and food and housing [81]. The extended examples are provided in the comparative analysis placed in supplementary materials (see comparison_analysis.xls and taxonomy.xls). Limiting only to identified domains or the lack of given ones does not cross through the usage but informs of the verified areas of practical application.
- The aim of the approach conveys the short description of the main features, objectives and assumptions. It was conceived on the basis of the analysis of the paper's content. This property provides the key knowledge of each of the selected solutions. To characterize a given set of approaches the main features are included, especially distinguishing a given set. The set

of indicators points out of the activities referring to evaluation of a degree of products [85], operations [43], whereas the set of measures emphasizes the basic background of measurements, including production [49] or processes [62]. Generally, the framework's aim is to ensure the guideline of how to integrate different sustainability aspects [86], assisting selected processes [12], or supplying sets of specified indicators for a given purpose [1].

- The type of gathering knowledge/data describes the possible methods of gathering the information mentioned in [20,80]. For example, [11,48,49] indicated a literature review as a basis for data collection. In the same context, an analysis is used in [87–89]. Exploitation of multiple datasets and benchmarks was mentioned in [11,61]. Similar to measures, these properties are covered by methods [15,80], frameworks [43,78] and indicators [12,29]. The additional properties were derived from [8,67] using questionnaires [90], desk-analysis and semi-structured interviews [84] and surveys [12]. Using experts to gather data was explained in [66,86]. Elaborating this property allowed to distinguish the main attributes characterizing this process.
- Exploitation of other solutions provides the information of used or developed approaches. For the set of metrics, the exploitation of the hierarchical metrics system takes place [11]. ISO standards are used for selected methods [15,80]. More complex approaches contain the collections of indicators, frameworks, or measures [14]. In indicator groups, using the AHP-entropy weight method created a new hybrid evaluation method [66]. Similarly, in factors, a conceptual formwork of the study was adopted from [91]. Then, in frameworks, the exploitation encompasses the holistic knowledge management approach [33]. Some of the solutions (i.e., frameworks) enhances the existing tools and methods [15].
- Additional information offers extra knowledge about the analysed approaches. This property adds a more detailed description of the solutions, i.e., offered features [66] and expected outcomes [14,24], as well as the particulars of the suggested applications [15], preferred aspects of assessment [12,43], or general destination [11]. This property's aim is to complement the previous section (see the aim, above).
- Divisions/subcategories/levels/key components refer to the existing divisions of the available solutions. This part contains the detailed information of the fragmentation of a given approach. It depends on the destiny of a given form and is linked with the property called the domain of usage. The particular sets differentiate with respect to the destination and applicability. For instance, the generic internal process, material, waste, recycling, pollution, cost [48,49], life cycle assessments, social life cycle assessments [27], consumer behaviours [87–89], material intensity, energy intensity, water consumption and toxic emissions [62] are common for most measures. Furthermore, the indicators cover some aspects of sustainability dimensions, providing specific subcategories (descriptive, performance, efficiency, sustainable reference values, production, regulatory, accounting, economic, quality and ecological indicators) [12,25]. Instead, the frameworks serve the following divisions: performance management, strategic thinking, corporate level strategy [92], risk management, energy use, power plants, industry [93], resource use, resource efficiency and environmental impacts [26]. It seems that some of the framework's divisions and subcategories may cover the chosen one from the measures.
- Types can be treated as extended version of the previous property: divisions/subcategories/levels/key components, providing more details about the attributes. This property provides specified information of the attributes. Some attributes refer to supplier aspects [48,49] and assumptive strategies and management [55], whereas the methods yield the particulars of input and output attributes [15]. Some environmental attributes (i.e., resource usage, emissions waste and effluents) are considered by indicators [43,66]. This set also reveals the details of the form of description (i.e., qualitative and quantitative indicators) [12] and purpose (i.e., fundamental, general and leading indicators) [85]. The framework's types encompass the knowledge about more specified attributes, directly referred to the applied field, i.e., material stage, manufacturing

stage, use stage [15], transport, energy use [93], or supply chain management [86]. Similar to divisions/subcategories/levels/key components property, some of the framework's divisions and subcategories may cover the chosen one from the measures. Due to a number of detailed attributes, more information can be found in the supplementary material (see comparison_analysis.xls).

- Dimensions are generally based on the three basic dimensions of sustainability: social, environmental and economic. Other existing forms, such as institutional [66] or cultural [35], broaden this property. The aim of this property is to provide the information of the destination of the particular form. Mostly, more than one dimension is identified in all of the analysed sets, i.e., [8,33,35]. Assigning the dimensions took place on the basis of the indicated attributes in the analysed papers and the information provided by the other authors.
- Limitations were drawn from the described shortcomings in the reviewed papers. Additional knowledge was derived from the comparative analyses presented as an example in [1,3,9]. This property informs of the possible constrains, especially including limitations of the method focusing on definitions and measures [48,49], a number of judged metrics [11], or ignorance both of systemic ecological services [90] and timing of processes and their release or consumption flows [15]. Furthermore, some methods are not useful for a given situation, i.e., budget allocation [82], whereas other approaches need further development [40]. Another inconvenience may concern the difficulties related to a not fully completed review excluding the analysis of some elements [14], a restricted area of application [33,67] and a low level of complexity [43]. Thus, the lack of a scientific basis for the attribution of different weights to the indicators [42] and the lack of integration of the approaches with sustainability strategy [12] concurs to mark other restrictions.
- The level of reliability/lack of the approaches contain the information of trustworthiness of the analysed solutions. Some metrics pointed to the lack of analysis focusing on selected fields, i.e., logistics or transportation [48,49], purchasing and supply [14] and sustainable consumption [8]. Furthermore, the chosen approaches may strongly favour environmental aspects, as well as quantifiable indicators that may not be practical in all operational practices [43] or are neglected. Moreover, in some cases, the resolution and level of detail of the studies can vary depending on the resources and time available, depending on the potential application of the research results [90]. This property also contains the information of the lack of empirical tests of the given approaches, including the development of appropriate social monitoring and reporting processes [33]. Considering only single metrics providing potentially false conclusions [80] is another identified shortcoming. Furthermore, some evaluation results are relatively intuitive and rational, at least to some degree [66]. The deep analysis of this property emphasizes its validity in the context of the practical application of a given approach. Often enough the knowledge of the level of reliability, or the lack of the particular form of approach, conditions the final result of the successful sustainability assessment.
- A dedicated group of users. Identifying the acceptable groups of users was elaborated on the basis of the information drawn from the description and the purpose of a given approach. Finally, the identified groups of users encompass both the people acting, i.e., suppliers [49], customers [48], stakeholders [15] and business entities, i.e., companies [81], organizations [87], institutions [93] and industries [67]. From the purpose of stakeholders, distinguishing public, private and community stakeholders [33]. Grouping the public sector contains government [26] and local authorities [12]. Groups of users were joined together on the basis of their existing similarities. Recognizing the various groups of users defines the target set of attributes.
- Challenges were elaborated on the basis of the recommended future research directions or suggested development provided in the reviewed papers. Predominantly, the suggestions of improvements of methods, metrics and frameworks are recommended. For instance, supporting the new applications and adaptation of a given methodology is suggested by [90]. Further, the challenge of optimizing for a larger number of objectives is shown in [11]. Some approaches imply the construction of supported tools, i.e., construction of social life cycle assessment (SLCA)

tools [15], or integration of tools for improving competitiveness in the marketplace by identifying risks and opportunities early [80].

The set of properties presented above has the essential properties which have the fundamental meaning for the sustainability assessment processes. Identifying the following eleven properties: domain/dedicated to, aim, type of gathering knowledge/data, exploitation of other solution, additional information, divisions/subcategories/levels/key components/types, dimensions, limitations, level of reliability (lacks the approach), dedicated group of users and challenges enables the comprehensive, multi-dimensional analysis of the sets of selected approaches. The provided analysis comprises the set of measures, metrics, frameworks, factors, tools, indicators and methods. The particular information of the given set was gathered in the supplementary materials (see comparison_analysis.xls and taxonomy.xls). When analysing the set of frameworks, it is remarkable that they are applied in the manufacturing sector, transport and resource management, whereas the measures mostly are used in purchasing, supply management, material utilization. Instead, indicators, for the most part, are employed in production, supply chain management, energy and material use, financial, or production areas. The complete comparison containing the full set of analysed approaches is provided in the supplementary material (see comparison_analysis.xls).

Overall, 44 approaches were selected and analysed. The comparison analysis contains a short description of the selected approaches, providing the details of the aim, complemented by the additional information, exploitation of other solutions and key components. In some cases, the analysis provides the information of the type of gathering knowledge and data. It also offers the information of dedicated groups of users. Moreover, the details of occurred limitations, level of reliability, shortages and challenges are provided. The whole comparison analysis is included in the supplementary material (see comparison_analysis.xls).

3.2. Main Assumptions of Knowledge Systematization for the Sustainability Assessment Domain

The process of collection and further categorization, of the information of the sustainability assessment approaches transformed the knowledge from the unstructured form into the semi-structured form. This was a basis to provide a formal description of the domain knowledge. In order to achieve this, set theory was used to ensure the detailed mathematical depiction. For this purpose, on the basis of the specific characteristics of the sets of properties presented above (see Section 3.1), the mathematical background of set theory is shown below.

In the domain and range of a relation, if R is a relation from set Tp and P, then the set of all taxons (all of the first components of the ordered pairs) belonging to R is called the domain of R. Thus, Dom is defined as follows:

$$(R) = \{tp \in Tp: (tp, p) \in R \text{ for some } p \in P\} \quad (1)$$

The set of all second components of the ordered pairs (the set of all taxons) belonging to R is called the range of R. Thus, the range of R is defined as follows:

$$R = \{p \in P: (tx, p) \in R \text{ for some } tx \in T\}. \quad (2)$$

If type Tp and properties P are two non-empty sets, then the Cartesian product T of Tp and P, denoted Tp × P, is the set of all ordered pairs (tp, p) such that tp ∈ Tp and p ∈ P:

$$Tp \times P = \{(tp, p): tp \in Tp, p \in P\}, \quad (3)$$

Properties P contain the finite set of taxons, defined as follows:

$$P = \{Cx, D, DoU, G, S, DF, Is, U\}, \quad (4)$$

where Cx is the complexity, D is the dimension, DoU is the domain of usage, G refers to the gathering data, DF are the development factors, Is are the issues and U refers to dedicated group of users.

Type Tp contains the finite set of taxons, which are subsets:

$$\text{Tp: \{M, F, I, Me, Tx, Mo, In, Fa\}}, \tag{5}$$

where M are measures, Me are methods, In are indices, Mo is a model, Fa are factors, Tx is a taxonomy, I are indicators and F are frameworks.

Measures M are the subset of Tp, containing the finite set of taxons:

$$M: \{M_{PS1}, M_{PS2}, M_{I1}, M_{I2}, M_{I3}, M_{CH}, M_{O}\}, \tag{6}$$

The set of taxons is given as follows: M_{PS1}, M_{PS2} refer to purchasing and supply management sustainability measures; M_{I1}, M_{I2}, M_{I3} are impact/intent-based measurement; M_{CH} are metrics assessing chemical processes; and M_{O} are overall assessing metrics.

Methods Me contain the finite set of taxons, which is given as follows:

$$Me: \{Me_{O}, Me_{PC}, Me_{LC1}, Me_{LC2}\}, \tag{7}$$

where Me_{O} are overall assessing methods; Me_{PC} are production and consumption assessing methods; and Me_{LC1}, Me_{LC2} are life cycle assessing methods.

Let indices In be a finite set of objects, which is given as follows:

$$In: \{In_{GSF}\}, \tag{8}$$

where In_{GSF} is the gross social feel-good index.

Model Mo is a finite set of objects, which includes the following taxons:

$$Mo: \{Mo_{T}\}, \tag{9}$$

where Mo_{T} is a model dedicated to the tourism sector.

Factors Fa contain a finite set of objects, where:

$$Fa: \{Fa_{SME}\}, \tag{10}$$

where Fa_{SME} refers to the factors assessing SE in SME.

Let taxonomies Tx be a finite set of objects. A taxonomy Tx consisting of a system of taxons, which are subsets Tx, is given as follows:

$$Tx = \{Tx_{SME}, Tx_{PS}\}, \tag{11}$$

where Tx_{SME} contains taxonomy-assessing SME strategies and Tx_{PS} is a taxonomy assessing purchasing and supply measures.

Indicators I contain a finite set of taxons:

$$I: \{I_{CH}, I_{S}, I_{C}, I_{GP}, I_{O}\}, \tag{12}$$

where I_{CH} are indicators assessing chemical processes and production, I_{S} are indicators assessing society, I_{C} refers to indicators assessing community sustainability, I_{GP} are indicators assessing the green degree of products and I_{O} contains indicators assessing the overall aspects.

Let frameworks F be a finite set of taxons:

$$F: \{F_{SE}, F_{S}, F_{C}, F_{SC}, F_{HE}, F_{I1}, F_{I2}, F_{R}, F_{P}, F_{UD1}, F_{UD2}, F_{LC}, F_{O1}, F_{O2}, F_{O3}, F_{O4}, F_{O5}, F_{O6}, F_{O7}, F_{O8}, F_{O9}, F_{O10}, F_{O11}\}, \tag{13}$$

where F_{SE} is a framework assessing SE; F_S is a framework assessing social aspects; F_C is a framework assessing cultural aspects; F_{SC} contains a framework assessing supply chain management; F_{HE} encloses a framework assessing human and environmental relationships; F_{I1} and F_{I2} are frameworks assessing industry processes; F_R is a framework assessing resources consumption; F_P refers to a framework assessing performance; and F_{UD1} and F_{UD2} reflect the undefined domain. Next, F_{LC} is a framework assessing the life cycle and F_{O1}–F_{O11} are overall assessing frameworks.

3.3. Knowledge Engineering for the Sustainability Assessment Domain

The main role of the exploitation of a knowledge base is to support the finding and reusing of relevant knowledge [94]. Further, the generally-accepted approach for structuring the domain knowledge is constructing domain ontologies to model concepts and relationships [95,96]. Ontologies offer a wide spectrum of opportunities, in particular, providing a common understanding of specific domains that can be communicated between people and application systems. The best-known definition of ontology was proposed by Gruber [97], who defines ontology as an explicit specification of a conceptualization. Ontology is usually expressed as a formal representation of knowledge by a set of concepts within a domain and the relationship between these concepts. Relatively, ontology-based modelling is a well-known approach to support both knowledge integration and interoperability between information technology systems during collaborative business processes [96,98]. Moreover, to cope with the complexity of engineering knowledge [96,99] in the sustainability assessment domain, ontology design is proposed as a promising approach. Modular ontology development implies that rather than having an enormous ontology to cover a given domain, it is necessary to abstract and generalize concepts into separate ontologies. This will be helpful to ensure better reusability, flexibility and maintainability [96] in the sustainability assessment domain.

3.3.1. Taxonomy Construction Process

The first step of knowledge engineering is the taxonomy construction stage. The foundation for a taxonomy construction was an in-depth analysis of selected approaches for sustainable assessment and measurement. The literature review allowed identifying the sets of properties. They were organized in a hierarchical form, including the main criteria and sub-criteria, distinctive for a given group. The approaches were organized into groups referring to the offered features. Nonetheless, in several papers, authors indicated the group a given approach belongs to. The process of gathering knowledge has the aim to verify this classification but oftentimes for a given group it was unfeasible to match the information to a proposed set of features.

The core premises of the taxonomy construction encompass the necessity of providing a comprehensive approach as a response to the lack of a manageable multi-dimensional approach. The shortcoming of guidelines and information of requirements related to given approaches for sustainability assessment concurs to elaborate the principles of classification. Furthermore, the various types of approaches for sustainability assessment will not always be suitable for all businesses. Thus, gathering knowledge in a holistic approach may support the adaptation of a company strategy to this process.

The proposed taxonomy is dedicated to the sustainability assessment domain. It contains the sets of measures, metrics, frameworks, tools, indicators and methods. The overall set of criteria was designed as a result of comprehensive analysis of the collected information about approaches which are presented in detail in Section 3.1. Selecting the best approach is a significant step to ensure the efficiency of the sustainability assessment process. Indeed, considering the variety of approaches and their features and performance, a formal classification of an approach for sustainability assessment domain knowledge is essential. From a formal point of view, the taxonomy can be described using set theory.

The taxonomy contains 44 approaches. The taxonomy includes the set of eight properties and 98 sub-properties. The number of properties is constructed as follows: type, complexity, dimensions of sustainability, domain of usage, gathering data, scope, identification of sustainable development factors, issues and receivers. Each set of properties comprises the sub-sets, according to the following frequency: types: measure/metric, indicator, framework, taxonomy, other, method, factors and tools; complexity: single solution and dedicated to one group; dimensions of sustainability: basic dimensions: social, environmental and economic; and other dimensions: ecological, institutional, cultural; domain of usage: supply chain, purchasing, unspecified products, unspecified domain, all consumption areas, food, housing (energy and water), energy resources, chemical processes, manufacturing sector, tourism sector, industrial ecology, SME, transport, green degree evaluation, material use, air quality, cultural factors, real estate, production, management, waste production disposal, services, petrochemical sector, toxics, pollutant dispersion, greenhouse gas emission, ecological/ecosystem health, infrastructure, mobility, clothing, none of the above and social aspects; gathering data: literature review, expert participation/knowledge, questionnaires/interview, discourse analysis, multiple datasets and survey; scope: evaluation, classification/categorization, knowledge systematization, analysis, comparative analysis, waste production reduction/disposal, assessment, quantitative assessment, qualitative assessment, measurement of sustainability development, management performance, financial performance efficiency, research model and support in evaluation; issues: supplier performance, policies, organization and management systems, stakeholder relationships, organization context, employee performance, supplier and customer relations, social impact, employment practices, community relations, competitive advantage, quality of service, flexibility, resource utilization, innovation, sustainable consumption, consumer behaviour, natural resources, economic impact, environmental impact, improvements, company strategies, stimulating and assisting societies and green policy; and receivers: company, government, institution, customers/consumers, suppliers, organization, stakeholder and industry. The taxonomy is provided in supplementary materials (see taxonomy.xls).

The taxonomy includes multi-dimensional aspects of sustainability assessment. It provides both knowledge systematization for sustainability assessment approaches and offers a multi-dimensional view of them. The taxonomy is a basis for the ontology construction, which is presented in detail below.

3.3.2. Ontology Construction Process

Building the ontology is based on an incremental process starting by the identification of the main concepts from the identified approaches dedicated to the sustainability assessment domain. This process is followed by the extraction of all concepts, properties and relationships from the common meta-model to form the backbone of the ontology. Finally, expanding the extracted concepts to a set of criteria prosecutes to a taxonomy construction. The ontology was built using the Protégé (Stanford University, Stanford, USA) [100] application. The applied technology standard is OWL (Ontology Web Language). The source code (OWL/XML) is provided in the supplementary materials (see ontology_source_code.owl and ontology_source_code.txt)

The main structure of the proposed ontology is modelled in Protégé [100] software. The class Criteria takes a central place in the ontology (Figure 2). This class is detailed to define different sub-classes in detail: Issues, Dimensions of sustainability, Type of approach, Type of gathering knowledge data, Receivers, Complexity, Scope and Domain of usage.

The class Scope has the following set: comparative analysis, classification/categorization, knowledge systematization, measurement of sustainability development, assessment (qualitative assessment, quantitative assessment), waste production reduction/disposal, efficiency, management performance, support in evaluation, financial performance, research model, evaluation and analysis. The class Complexity includes two sub-classes: dedicated to one group and single solution. Then, the class Receivers contains the set of the dedicated group of users: company, organization, suppliers, customers/consumers, government, industry, institution and stakeholder. The class Type of gathering knowledge/data informs of the possible ways of collecting information such as: survey, report, expert participation/knowledge, multiple datasets, literature review, questionnaires/interview and discourse analysis. Further, the class Issues contains the specified sub-classes: improvements, community relations, innovation, policies organization and management systems, natural resources, organization context, competitive advantage, environmental impact, economic impact, stakeholder relationships, supplier and customer relations, company strategies, employee performance, green policy, resource utilization, social impact, sustainable consumption, employment practices, quality of service, supplier performance, consumer behaviour, stimulating and assisting societies and flexibility. Moreover, the class Domain of usage presents the aspects of applied areas, such as: housing/energy and water, clothing, air quality, services, SME, industrial ecology, transport, material use, cultural factors, pollutant dispersion, toxics, supply chain, waste production disposal, production, tourism sector, mobility, social aspects, ecological ecosystem health, petrochemical sector, greenhouse gas emission, management, manufacturing sector, infrastructure, purchasing, energy resources, chemical processes, all consumption areas, real estate, none of above and food. The sub-class called Type of approaches distinguishes the considered types of analysed solutions: Measure, Taxonomy, Method, Other, Framework, Indicator and Tool (Figure 3).

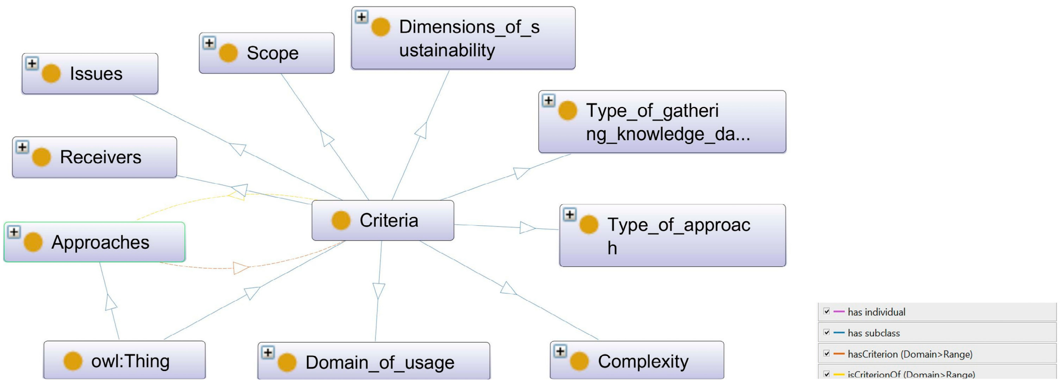

Figure 2. Design of the class Criteria of the SA ontology.

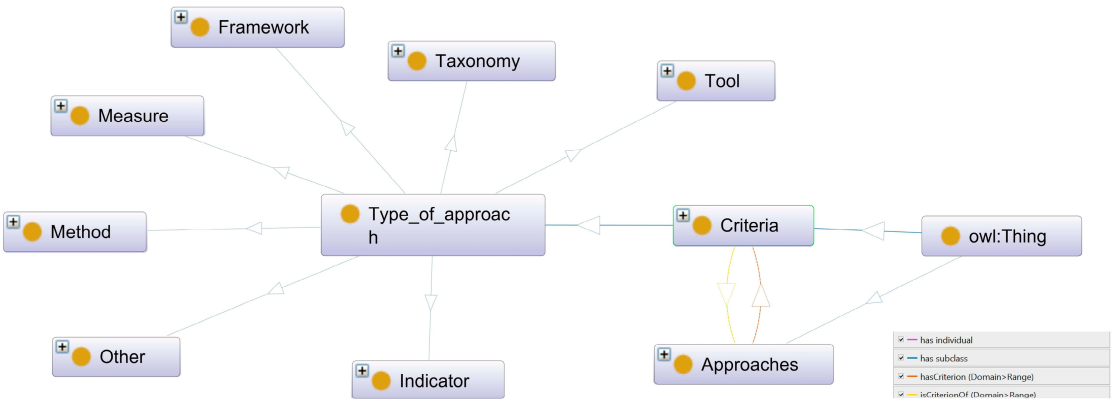

Figure 3. Exemplary sub-class called Type of the approaches of the SA ontology.

Consequently, this sub-class contains the detailed information of the belonging of an approach to a given group. For example, the sub-class Indicator describes the approaches categorized to this group (Figures A1 and A2, see Appendix A).

The class Approaches has a sub-class Name of Approach, which contains the set of various solutions dedicated to sustainability domain assessment: in-house, best performance value indicators, environmental sustainability measures, sustainable entrepreneurship knowledge based model, impact-based assessment instruments, a taxonomy of sustainable purchasing and supply measures, DPSIR framework, metrics assessing chemical processes, taxonomy of some strategies, integrated sustainability assessment indicator system, Sustainable Society Index (SSI), intent-based measurement instruments from environmental psychology, a framework determining governmental progress in SD, Hofstede's cultural framework, an integrative framework for the selection of relevant behaviours, ecological footprint method, factors influencing sustainable entrepreneurship in SMEs, a framework of sustainable SCM, Global Reporting Initiative (GRI) framework, US Interagency Working Party on Sustainability, methodological framework for sustainability assessment, social sustainability framework, operational sustainability framework, UNCSD framework, a proposed research model of SE, Comprehensive sustainability index GSF, hierarchical metrics system, social sustainability measures, input-output-outcome-impact, sustainability performance management system, European Conceptual Framework for Social Indicators, life cycle costing (LCC), a framework for social life cycle impact assessment, framework assessing the social sustainability of engineering projects and technologies, intent-based measurement instruments from consumer behaviour research, life cycle assessment (LCA), Wuppertal Sustainability Indicators, DESIRE's conceptual framework, Sustainability Metrics of the Institution of Chemical Engineers, a set of different types of indicators, eco-efficiency analysis (EEA), quality of life, the Sustainability Reporting Guidelines, fundamentals and general and leading indicators (Figure 4).

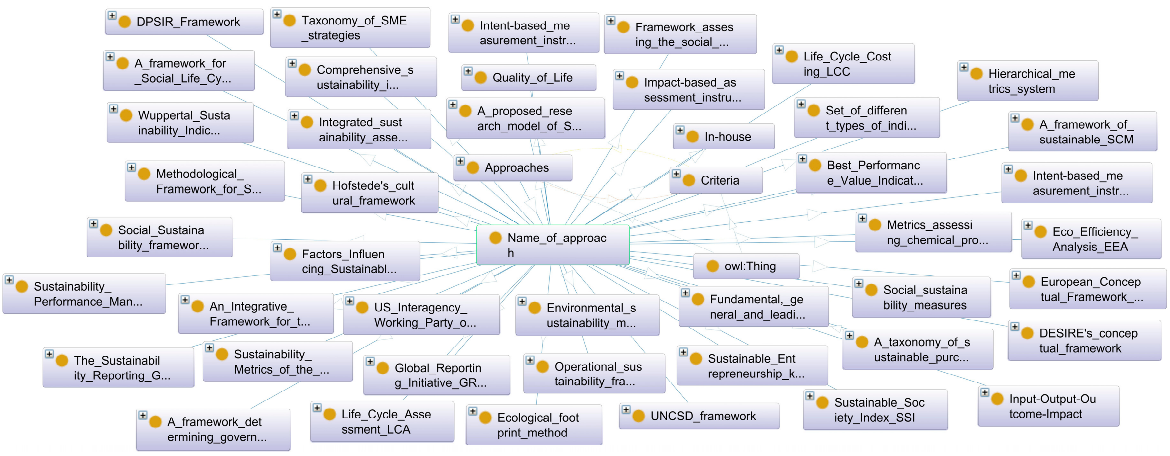

Figure 4. Typology of selected SA approaches.

3.3.3. Ontology for Sustainability Assessment: Formal Description

The proposed ontology is implemented using OWL. It provides a formal and structured method to handling the SA domain knowledge. Referring to Figure 1, the formal description is the step enabling further activities of the created ontology.

Knowledge representation focuses on the design on formalism that are both epistemologically and computationally adequate for expressing knowledge [101] about the sustainability assessment domain. The usage of Description Logics (DL) is applied to encode syntactic, semantic and pragmatic elements needed to drive semantic interpretation [101]. Consequently, the formal description of presented knowledge representation allows for machine-readable processing, sharing, reuse and, finally, populating new knowledge. OWL, as well as DL, are machine-readable languages dedicated to extract meaningful, relevant and applicable information. The aim of the formal representation languages is to simplify the process of extracting and expressing the domain-specific knowledge in user-friendly and machine-readable forms. The formal representation captures domain knowledge about sustainability assessment and offers a wide spectrum to capitalize on the effects. The knowledge representation presented in this paper is publicly available (https://webprotege.stanford.edu/#projects/99888f55-c97d-471b-b992-bed90718b422). The formal description (ontology_source_code.owl) is attached in the Supplementary Material.

3.3.4. Ontology for Sustainability Assessment: Validation Stage Using Competence Questions

Following the presented ontology construction methodology on the Figure 1, validation of the proposed ontology checks its formal structure and coherence with the domain knowledge. In order to use the ontology from the knowledge repository, query algorithms are used to provide useful information at the end of the reasoning process. To investigate the correctness of the proposed ontology, the competence questions are constructed and implemented using a Description Logic query mechanism. This section describes the exemplary competence questions and verifies their utility in retrieving information with response to the user's needs. Correctness of the obtained results confirms the validation process and, consequently, provides the set of results.

The sustainability assessment ontology is based on the related set of presented criteria and the approaches, including the specified relations between them. The proposed classification supports the rapid identification of the main attributes according to the sustainability assessment domain. Further, the approach specifications give the main characteristics of the selected solution. From the technological point of view, each approach has distinguished features, implemented in the ontology. Supporting ontology designers or engineers to correctly introduce new solutions in the knowledge repository ensures the proper quality of the proposed model and helps in more easily identifying the best sustainability assessment approaches to the user's needs.

It is a principle of the solution to provide the requested features by the sustainability assessment approach. In practice, this will help in the detection of the preferred solution, including constraints to be respected. The process of providing the preferred solutions starts with defining the approaches' specifications. Further, it requires the following activities to be completed: implementing the definitions, reflecting the necessary and sufficient conditions, enables providing the exemplary case studies dedicated to solving a given selection problem of sustainability assessment approach. In this context, some case studies were proposed to test the practical application of the ontology.

Validating the ontology allows to check both the consistency and correctness of the proposed ontology. To understand whether the ontology is coherent with the domain knowledge, some validation queries were posed to check its reliability. To investigate whether the ontology is capable to complete information retrieval and interoperability needs, the results have been compared to the knowledge included in the comparison analysis.

The case study focuses on the choosing the most efficient approaches including the set of features essential for the production company. Thus, following the proposed ontology, the definition containing the set of criteria was constructed as follows (Figure 5). The specification includes the criteria and sub-criteria: domain of usage: production, domain of usage: manufacturing sector, issues: environmental impact, scope: assessment, receivers: company, sustainability dimension: environmental dimension. Each of the criteria and sub-criteria should be fulfilled to belong to the final ranking.

The result is obtained from a number of implemented instances of approaches and by queries on capabilities offered by a Description Logic Query, implemented in Protégé software. The query was added manually by the engineers based on their expertise. Visualizing the final ranking of the solutions is presented in Figure 6.

Additional experimental queries have been posed to find the relevant approaches for the chemistry field, including the set of basic features important for a chemical company. This case study was conducted on the basis of the identification of the features influencing the environment in this area. It was found that the following criteria should be included: sustainability dimension: social dimension; sustainability dimension: environmental dimension; sustainability dimension: economic dimension; domain of usage: chemical processes; domain of usage: production; domain of usage: pollutant dispersion; domain of usage: petrochemical sector; domain of usage: industrial ecology; issues: environmental impact; issues: green policy; scope: assessment; and receivers: organization (Figure 7).

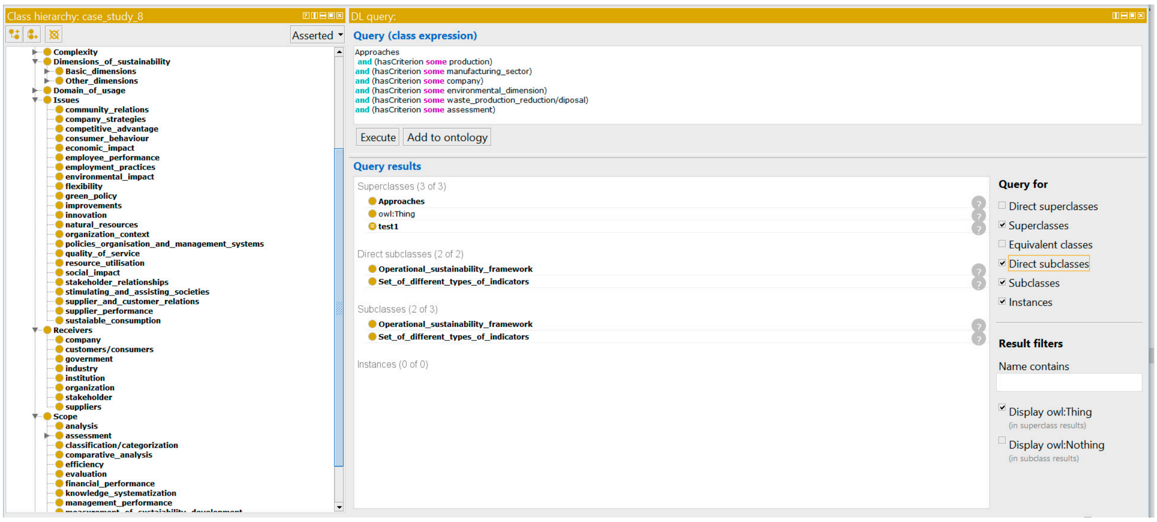

Figure 5. Results of using Description Logic query to extract SA approaches for production.

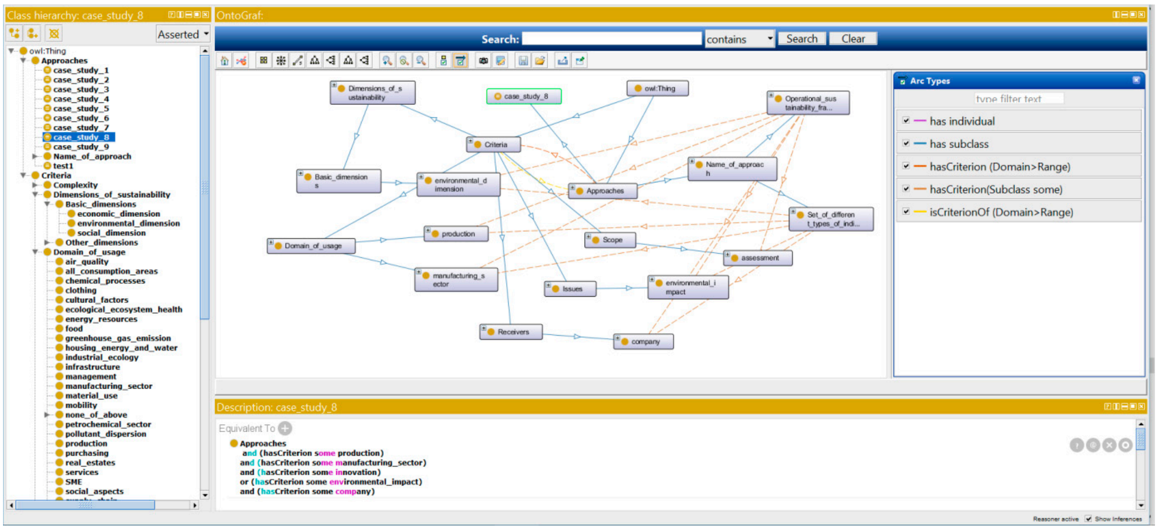

Figure 6. Visualizing query using Onto Graf in the ontology.

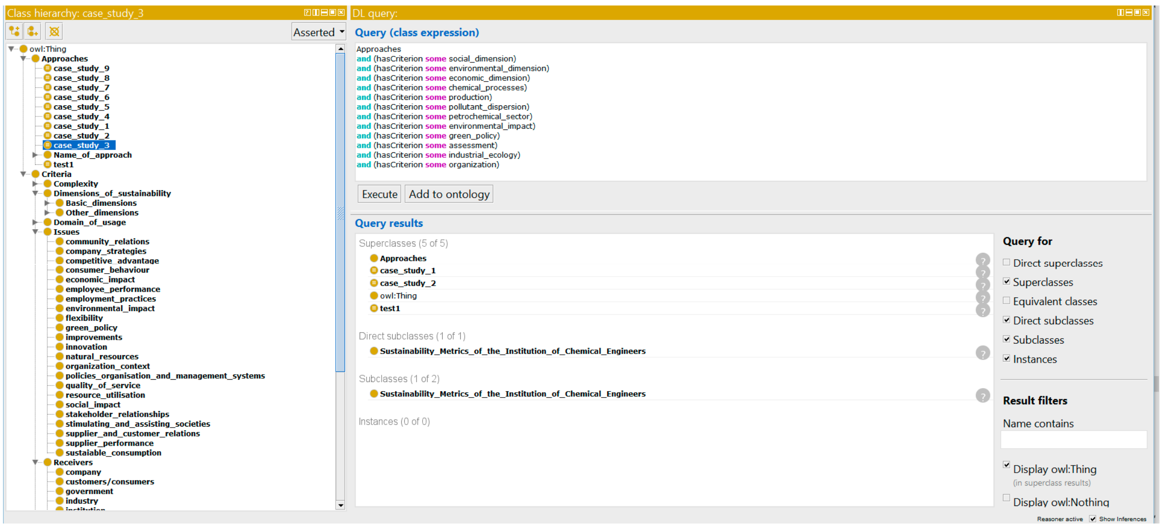

Figure 7. Results of using a Description Logic query to extract SA approaches for the chemistry field.

Defining the necessary and sufficient conditions and afterwards implementing them into the Protégé software, allows the reasoning process to be started. Based on the experimentation results, the final set of the approaches is obtained. In accordance with the constructed definition, only one solution matches these requirements (Figure A3, see Appendix A).

In this case study, it is possible to find relevant sustainability assessment approach with regard to its specification defined by a user (Figure A4, see Appendix A). Assuming that a user is looking for the solution that fulfils a set of pre-defined requirements—sustainability dimensions: environmental dimension, receivers: company, receivers: stakeholder, domain of usage: housing, energy and water, type of gathering data: multiple datasets, issues: environmental impact—the application of the reasoning mechanism provides a set of results with regard to these pre-defined requirements. In this case two approaches for sustainability assessment fulfil this defined set of criteria (Figure A5, see Appendix A).

4. Conclusions

The paper addressed compound problem the selection of a sustainability assessment approach. The choice of an approach depends on multiple diversified factors. Depending on which indicators, measures or metrics are used, the results of impact assessments can vary considerably in each of the sustainability dimensions. Furthermore, there is a clear demand to provide a set of comprehensive criteria characterizing the available approaches. Moreover, the process of gathering knowledge in a single place had to support both the process of selection of sustainability assessment approach and supplying a guidance how to use it. With regard to these issues, a domain knowledge conceptualization and formal foundations of a knowledge base for selection of a sustainability assessment approach were presented.

The analysis of the literature confirmed the lack of knowledge systematization in this field. In response to the presented shortcomings, the author developed an approach based on knowledge management, tailored for the sustainability assessment domain. Considering the specified characteristics of SA domain, a dedicated ontology has been developed for maintenance of the knowledge systematization, sharing and reuse. In this context, the challenge was to identify and verify the existing SA approaches, and, thereafter, implement them (on the basis of the prepared taxonomy) into the domain ontology.

The main intention of ontologies' creation is to capture and formalize a domain of knowledge. The ontology reported here attempts to do this within the domain of sustainability assessment (SA). In practical terms, the author proposes a reusable domain model of selected approaches to multi-usage, reusing and knowledge sharing and dissemination. The author's ontology is designed in a manner to be useful for the researchers, i.e., allow them to rapidly and intuitively find, any SA approaches in any of the major or minor model properties and, having found it, learn a considerable to a large extent about the SA and its relationships to other approaches. Additionally, the presented ontology also attempts to incorporate a great amount of information about these SA approaches and, therefore, is far more comprehensive in its detail than the source resources.

Additionally, the presented ontology provides independent knowledge and SA's unique features that can be incorporated into any database, knowledge base or information system holding knowledge associated to SA. The formalized structure of the ontology, along with the set of SA approaches, allows the users to incorporate the data oriented on sustainability measurement into their databases, integrate the data with the knowledge encapsulated in the ontology and use it to interoperate with other databases. Furthermore, the formal representation of knowledge was also provided. Offering a machine-readable access and handling semantic data is an interesting step to enhance the searching capacity and knowledge sharing of the proposed ontology. This form of problem solving ensures semantic interoperability for knowledge and data collected and may support the processes related to prediction, computation, meaningfulness across knowledge sources developed independently to meet diverse needs.

While summarizing the research presented, it should be noted that the main contributions include the following highlights:

- We carefully and systematically analysed the available sustainability assessment approaches and we gathered unstructured, semi-structured and structured knowledge about sustainability assessment approaches.
- We provide complete domain knowledge of SA solutions, both on unstructured and semi-structured knowledge forms, which can be directly applied by the experts in the process of SA evaluation.
- Based on aforementioned findings and using the knowledge engineering mechanisms, we also propose a structured, ontology-based knowledge model for sustainability assessment domain, at the same time providing a reusable and publicly available SA formal model and its complete logical description.
- We verify consistency of the obtained knowledge model using competency questions.

During the research, some possible areas of improvement of the presented knowledge model and future work directions were identified. It seems to be interesting to extend the presented knowledge base using the formal background of particular sustainability assessment approaches. Moreover, the presented knowledge model could be bridged with references' use cases model, at the same time providing detailed practical description of all of the analysed approaches. Another interesting future work may concern the attempt of effectiveness evaluation of particular SA approaches, both in context of application areas and use cases. Technically, a semantic integration with external reference knowledge sources using semantic annotations mechanisms could be a challenging task.

Last but not least, it should be noted that, similar to other available resources, although this ontology contains all the common SA types, it is not complete. As with other research community resources and initiatives, the community input is essential for the development and maintenance of the SA ontology and therefore the readers are welcome to contribute to the ontology, by using the provided link.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/10/2/300/s1; OWL code of the ontology: ontology_source_code.owl, ontology_source_code.txt; conceptual_model.xls; comparison_analysis.xls; taxonomy.xls (see [102–111]).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

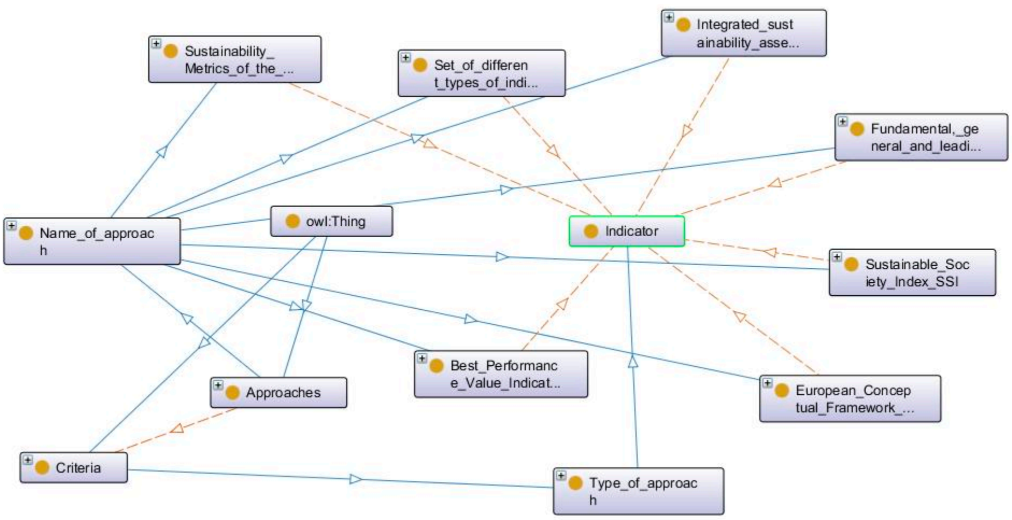

Figure A1. Specification of a selected sub-class called "Indicators."

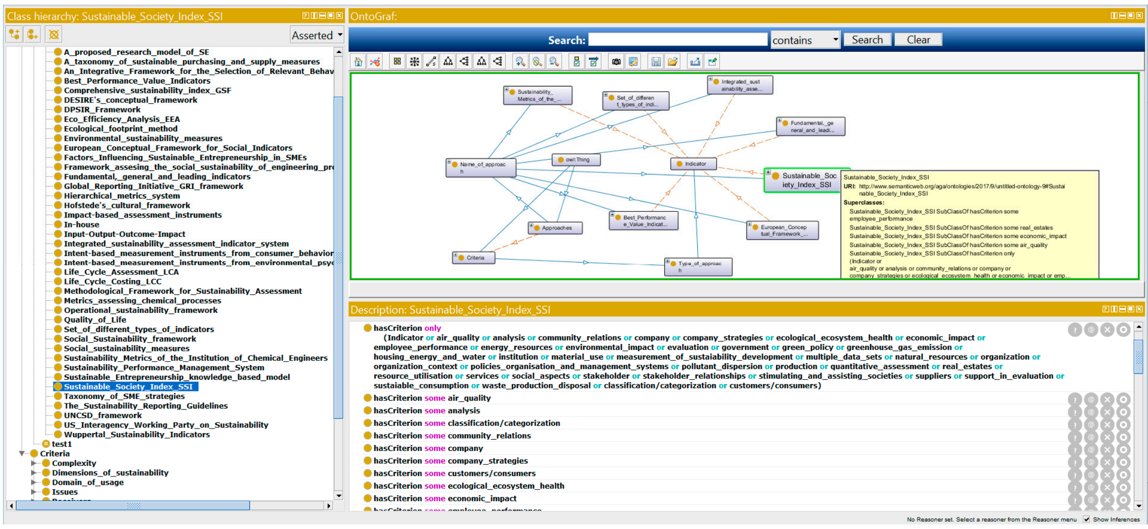

Figure A2. Detailed specification of a selected sub-class called "Indicators."

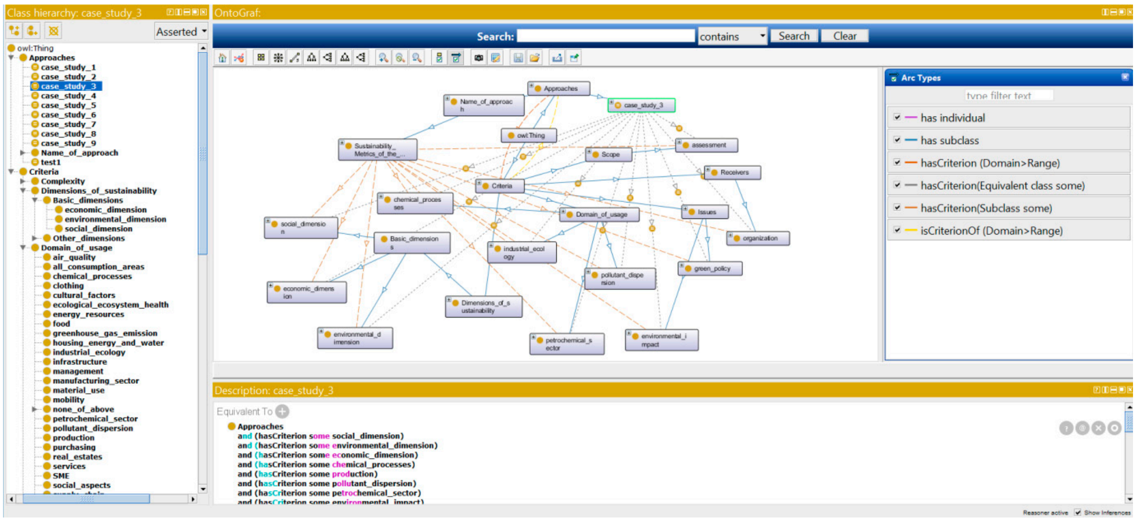

Figure A3. Visualizing query using Onto Graf in the ontology.

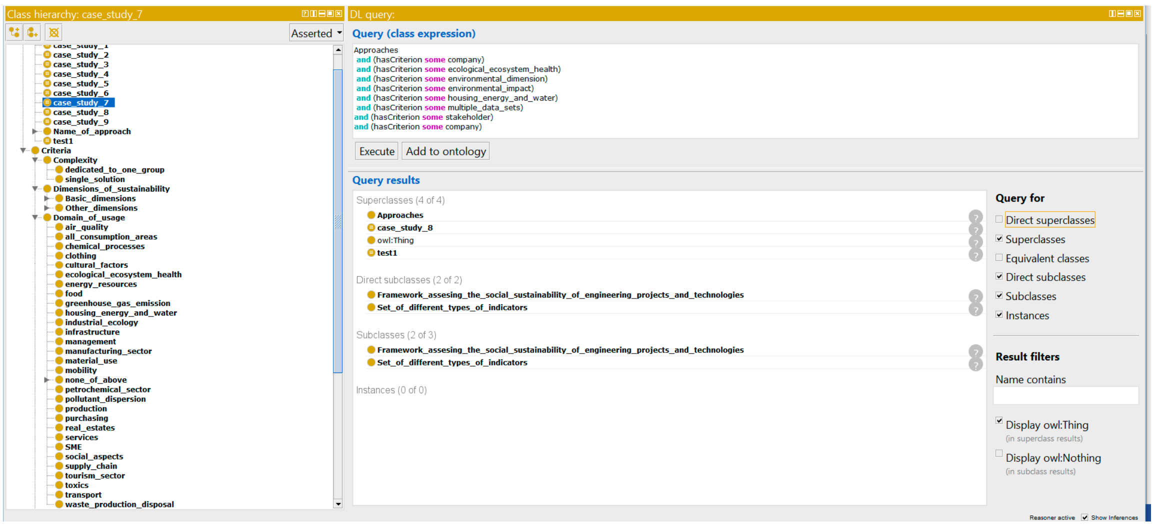

Figure A4. Results of using Description Logic query to extract SA approaches.

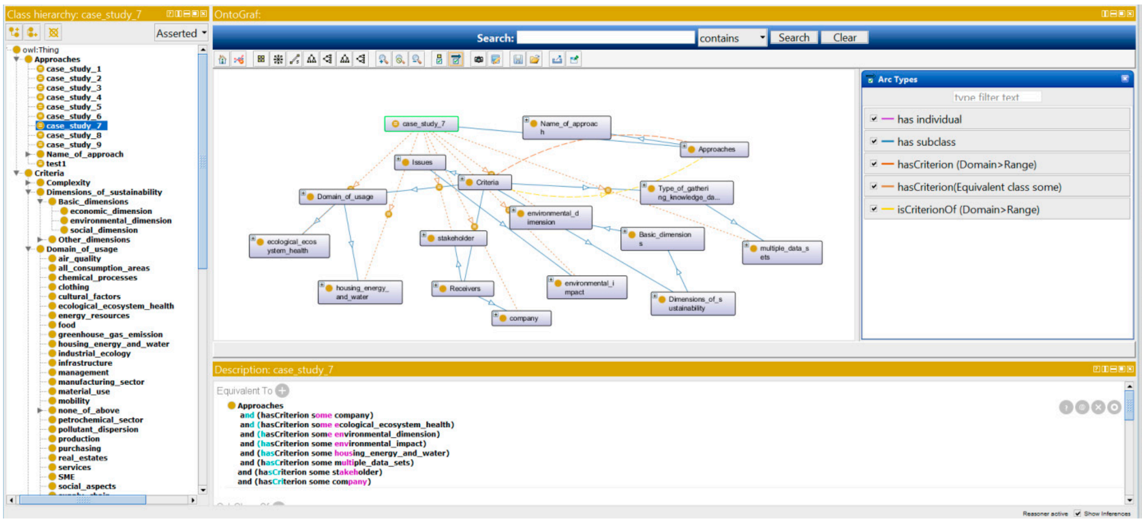

Figure A5. Visualizing query using Onto Graf in the ontology.

References

1. Labuschagnea, C.; Brenta, A.C.; Ron, P.G.; Van Ercka, P.G. Assessing the sustainability performances of industries. *J. Clean. Prod.* **2005**, *13*, 373–385. [CrossRef]
2. Jansen, R. *Multi-Objective Decision Support for Environmental Management*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1992; p. 248, ISBN 0-7923-1908-7.
3. Sala, S.; Ciuffo, B.; Nijkamp, P. A systemic framework for sustainability assessment. *Ecol. Econ.* **2015**, *119*, 314–325. [CrossRef]
4. Devuyst, D.; Hens, L.; de Lannoy, W. *How Green Is the City? Sustainability Assessment and the Management of Urban Environments*; Columbia University Press: New York, NY, USA, 2001; pp. 457–466, ISBN 9780231118033.
5. Verheem, R. Recommendations for Sustainability Assessment in the Netherlands. In *Environmental Impact Assessment in the Netherlands. Views from the Commission for EIA in 2002*; Netherlands Commission for EIA: Utrecht, The Netherlands, 2002.
6. Wackernagel, M.; Rees, W. *Our Ecological Footprint: Reducing Human Impact on the Earth*; Electronic New Society Publishers: Philadelphia, PA, USA, 1996; p. 160, ISBN 0-86571-312-X.
7. Kates, R.W.; Clark, W.C.; Corell, R.; Hall, J.M.; Jaeger, C.C.; Lowe, I.; McCarthy, J.J.; Schellnhuber, H.J.; Bolin, B.; Dickson, N.M.; et al. Environment and development. Sustainability science. *Science* **2001**, *292*, 641–642. [CrossRef] [PubMed]
8. Geiger, S.; Fischer, D.; Schrader, U. Measuring What Matters in Sustainable Consumption: An Integrative Framework for the Selection of Relevant Behaviors. *Sustain. Dev.* **2017**. [CrossRef]
9. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. An overview of sustainability assessment methodologies. *Ecol. Indic.* **2012**, *15*, 281–299. [CrossRef]
10. Hermann, B.G.; Kroeze, C.; Jawjit, W. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. *J. Clean. Prod.* **2007**, *15*, 1787–1796. [CrossRef]
11. Sikdar, S.K. Sustainable Development and Sustainability Metrics. *AIChE J.* **2003**, *49*, 1928–1932. [CrossRef]
12. Warhurst, A. *Sustainability Indicators and Sustainability Performance Management*; Report to the Project: Mining, Minerals and Sustainable Development (MMSD); International Institute for Environment and Development (IIED): Coventry, UK, 2002.
13. Briassoulis, H. Sustainable development and its indicators: Through a (planner's) glass darkly. *J. Environ. Plan. Manag.* **2001**, *44*, 409–427. [CrossRef]
14. Miemczyk, J.; Johnsen, T.E.; Macquet, M. Sustainable purchasing and supply management: A structured literature review of definitions and measures at the dyad, chain and network levels. *Supply Chain Manag.* **2012**, *17*, 478–496. [CrossRef]

15. Dreyer, L.C.; Hauschild, M.Z.; Schierbeck, J. A framework for social life cycle impact assessment. *Int. J. Life Cycle Assess.* **2006**, *11*, 88–97. [CrossRef]
16. Moldan, B.; Janoušková, S.; Hák, T. How to understand and measure environmental sustainability: Indicators and targets. *Ecol. Indic.* **2012**, *17*, 4–13. [CrossRef]
17. United Nations. *Human Development Report*; United Nations: New York, NY, USA, 2001; Available online: http://www.undp.org (accessed on 22 September 2017).
18. Bohringer, C.; Jochem, P.E.P. Measuring the immeasurable—A survey of sustainability indices. *Ecol. Econ.* **2007**, *63*, 1–8. [CrossRef]
19. Jung, E.J.; Kim, J.S.; Rhee, S.K. The measurement of corporate environmental performance and its application to the analysis of efficiency in oil industry. *J. Clean. Prod.* **2001**, *9*, 551–563. [CrossRef]
20. Jackson, T. Sustainable consumption. In *Handbook of Sustainable Development*; Atkinson, G., Dietz, S., Neumeyer, E., Eds.; Elgar: Cheltenham, UK, 2007; pp. 254–268, ISBN 978-1-84844-472-0.
21. Hertwich, E.G. Life cycle approaches to sustainable consumption: A critical review. *Environ. Sci. Technol.* **2005**, *39*, 4673–4684. [CrossRef] [PubMed]
22. Heiskanen, E.; Mont, O. Power KA map is not a territory—Making research more helpful for sustainable consumption policy. *J. Consum. Policy* **2014**, *37*, 27–44. [CrossRef]
23. Holden, E.; Linnerud, K.; Banister, D. The imperatives of sustainable development. *Sustain. Dev.* **2016**, *25*, 213–226. [CrossRef]
24. Wang, T.-K.; Zhang, Q.; Chong, H.-Y.; Wang, X. Integrated Supplier Selection Framework in a Resilient Construction Supply Chain: An Approach via Analytic Hierarchy Process (AHP) and Grey Relational Analysis (GRA). *Sustainability* **2017**, *9*, 289. [CrossRef]
25. Teece, D.J. Explicating dynamic capabilities: The nature and microfoundations of (sustainable) enterprise performance. *Strateg. Manag. J.* **2007**, *28*, 1319–1350. [CrossRef]
26. Eisenmenger, N.; Giljum, S.; Lutter, S.; Marques, A.; Theurl, M.C.; Pereira, H.M.; Tukker, A. Towards a Conceptual Framework for Social-Ecological Systems Integrating Biodiversity and Ecosystem Services with Resource Efficiency Indicators. *Sustainability* **2016**, *8*, 201. [CrossRef]
27. Dholakia, R.; Wackernagel, M. *The Ecological Footprint Questionnaire*; Redefining Progress: San Francisco, CA, USA, 1999.
28. Bebbington, J.; Brown, J.; Frame, B. Accounting technologies and sustainability assessment models. *Ecol. Econ.* **2007**, *61*, 224–236. [CrossRef]
29. Veleva, V.; Ellenbecker, M. Indicators of sustainable production: Framework and methodology. *J. Clean. Prod.* **2001**, *9*, 519–549. [CrossRef]
30. Kuik, O.J.; Gilbert, A.J. Indicators of sustainable development. In *Handbook of Environmental and Resource Economics*; Van den Bergh, J.C.J.M., Ed.; Edward Elgar: Cheltenham, UK, 1999; pp. 722–730, ISBN 978-1-85898-375-2.
31. Savić, D.; Veljko, J.; Petrovic, N. Rebuilding the Pillars of Sustainable Society Index: A Multivariate Post Hoc I-Distance Approach. *Probl. Ekorozw. Probl. Sustain. Dev.* **2016**, *12*, 125–134.
32. Sustainable Society Index (SSI). Available online: http://www.ssfindex.com (accessed on 18 September 2017).
33. Cuthill, M. Strengthening the 'social' in sustainable development: Developing a conceptual framework for social sustainability in a rapid urban growth region in Australia. *Sustain. Dev.* **2010**, *18*, 362–373. [CrossRef]
34. Spohn, O.M. *Sustainable Development Indicators within the German Water Industry—A Case Study*; Carried out at Chalmers University of Technology; Chalmers University of Technology: Gothenburg, Sweden, 2004.
35. Hofstede, G. Dimensionalizing Cultures: The Hofstede Model in Context. *Online Read. Psychol. Cult.* **2011**, *2*. [CrossRef]
36. Ranganathan, J. *Sustainability Rulers: Measuring Corporate Environmental & Social Performance*; Sustainable Enterprise Perspectives; World Resources Institute: Washington, DC, USA, 1998.
37. Lundin, U. Indicators for Measuring the Sustainability of Urban Water Systems—A Life Cycle Approach. Ph.D. Thesis, Department of Environmental Systems Analysis, Chalmers University of Technology, Göteborg, Sweden, 2003.
38. KEI, Knowledge Economy Indicators. *Work Package 7, State of the Art Report on Simulation and Indicators*; European Commission: Brussels, Belgium, 2005.
39. Berke, P.; Manta, M. *Planning for Sustainable Development: Measuring Progress in Plans*; Working Paper; Lincoln Institute of Land Policy: Cambridge, MA, USA, 1999.

40. Crnogaj, K.; Rebernik, M.B.; Hojnik, B.; Omerzel, G.D. Building a model of researching the sustainable entrepreneurship in the tourism sector. *Kybernetes* **2014**, *43*, 377–393. [CrossRef]
41. Meadows, D. *Indicators and Information Systems for Sustainable Development—A Report to the Balaton Group*; The Sustainability Institute: Hartland, WI, USA, 1998. Available online: http://www.sustainabilityinstitute.org/resources.html#SIpapers (accessed on 13 September 2017).
42. Van de Kerk, G.; Manuel, A. *Sustainable Society Index 2016*; Sustainable Society Foundation: The Hague, The Netherlands, 2016. Available online: http://www.ssfindex.com (accessed on 13 September 2017).
43. IChemE—Institution of Chemical Engineers, Institution of Chemical Engineers. *Sustainable Development Progress Metrics*. 2002. Available online: http://www.icheme.org/sustainability/metrics.pdf (accessed on 13 September 2017).
44. Hsu, A.; Zomer, A. Environmental Performance Index. Wiley StatsRef: Statistics Reference Online: 2016. pp. 1–5. Available online: http://onlinelibrary.wiley.com/doi/10.1002/9781118445112.stat03789.pub2/abstract (accessed on 23 December 2017).
45. Osberg, L.; Sharpe, A. International comparisons of trends in economic well-being. *Soc. Indic. Res.* **2002**, *58*, 349–382. [CrossRef]
46. Emerson, J.W.; Hsu, A.; Levy, M.A.; de Sherbinin, A.; Mara, V.; Esty, D.C. *Environmental Performance Index and Pilot Trend Environmental Performance Index*; Yale Center for Environmental Law and Policy: New Haven, CT, USA, 2012; pp. 1–99.
47. Tanzil, D.; Beaver, E.R.; Heine, L.; Abraham, M.A. Designing for Sustainability. In *Transforming Sustainability Strategy into Action: The Chemical Industry*; Beloff, B., Lines, M., Tanzil, D., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2005. [CrossRef]
48. Camison, C. Learning for environmental adaptation and knowledge-intensive services: The role of public networks for SMEs. *Serv. Ind. J.* **2008**, *28*, 827–844. [CrossRef]
49. Darnall, N.; Jolley, G.J.; Handfield, R. Environmental management systems and green supply chain management: Complements for sustainability? *Bus. Strateg. Environ.* **2008**, *17*, 30–45. [CrossRef]
50. Maignan, I.; Hillebrand, B.; McAlister, D. Managing socially-responsible buying: How to integrate non-economic criteria into the purchasing process. *Eur. Manag. J.* **2002**, *20*, 641–648. [CrossRef]
51. Holt, D.; Ghobadian, A. An empirical study of green supply chain management practices amongst UK manufacturers. *J. Manuf. Technol. Manag.* **2009**, *20*, 933–956. [CrossRef]
52. Carter, C.R.; Jennings, M.M. The role of purchasing in corporate social responsibility: A structural equation analysis. *J. Bus. Logist.* **2000**, *25*, 145–186. [CrossRef]
53. Eltayeb, T.K.; Zailani, S.; Jayaraman, K. The examination on the drivers for green purchasing adoption among EMS 14001 certified companies in Malaysia. *J. Manuf. Technol. Manag.* **2010**, *21*, 206–225. [CrossRef]
54. Koplin, J.; Seuring, S.; Mesterharm, M. Incorporating sustainability into supply management in the automotive industry: The case of the Volkswagen AG. *J. Clean. Prod.* **2007**, *15*, 1053–1062. [CrossRef]
55. Thun, J.R.-H.; Mueller, A. An empirical analysis of green supply chain management in the German automotive industry. *Bus. Strateg. Environ.* **2010**, *19*, 119–132. [CrossRef]
56. Rao, P.; Holt, D. Do green supply chains lead to competitiveness and economic performance? *Int. J. Oper. Prod. Manag.* **2005**, *25*, 898–916. [CrossRef]
57. Zhu, Q.; Sarkis, J.; Geng, Y. Green supply chain management in China: Pressures, practices and performance. *Int. J. Oper. Prod. Manag.* **2005**, *25*, 449–468. [CrossRef]
58. Vachon, S.; Mao, Z. Linking supply chain strength to sustainable development: A country-level analysis. *J. Clean. Prod.* **2008**, *16*, 1552–1560. [CrossRef]
59. Seuring, S.; Muller, M. From a literature review to a conceptual framework for sustainable supply chain management. *J. Clean. Prod.* **2008**, *16*, 1699–1710. [CrossRef]
60. Sustainability Index. Available online: https://www.aiche.org/ifs/resources/sustainability-index (accessed on 10 July 2017).
61. Ziemba, P.; Wątróbski, J.; Zioło, M.; Karczmarczyk, A. Using the PROSA Method in Offshore Wind Farm Location Problems. *Energies* **2017**, *10*, 1755. [CrossRef]
62. Schwartz, J.; Beloff, B.; Beaver, E. Use Sustainability Metrics to Guide Decision-Making. *Chem. Eng. Prog.* **2002**, *98*, 58–63.

63. Fiksel, J. Designing Resilient, Sustainable Systems. *Environ. Sci. Technol.* **2003**, *37*, 5330–5339. [CrossRef] [PubMed]
64. EUROSTAT: Sustainable Development Indicators. Available online: http://ec.europa.eu/eurostat/web/sdi/indicators (accessed on 13 August 2017).
65. Yang, W.; McKinnon, M.C.; Turner, W.R. Quantifying human well-being for sustainability research and policy. *Ecosyst. Health Sustain.* **2015**, *1*, 1–13. [CrossRef]
66. Wu, K.J.; Liao, C.J.; Tseng, M.L.; Lim, M.K.; Hu, J.; Tan, K. Toward sustainability: Using Big Data to Explore the Decisive Attributes of Supply Chain Risks and Uncertainties. *J. Clean. Prod.* **2017**, *142*, 663–676. [CrossRef]
67. Hosseininia, G.; Ramezani, A. Factors Influencing Sustainable Entrepreneurship in Small and Medium-Sized Enterprises in Iran: A Case Study of Food Industry. *Sustainability* **2016**, *8*, 1010. [CrossRef]
68. Bengtsson, M.; Steen, B. Weighting in LCA—Approaches and applications. *Environ. Prog. Sustain.* **2000**, *19*, 101–109. [CrossRef]
69. Batra, S. Sustainable Entrepreneurship and Knowledge Based Development. In Proceedings of the Eleventh International Entrepreneurship Forum, Kuala Lumpur, Malaysia, 3–6 September 2012; pp. 2–30.
70. Ireland, R.D.; Hitt, M.A.; Sirmon, D.G. A Model of Strategic Entrepreneurship: The Construct and its Dimensions. *J. Manag.* **2003**, *29*, 963–989. [CrossRef]
71. Belkadi, F.; Alain, B.; Florent, L. Knowledge Based and PLM Facilities for Sustainability Perspective in Manufacturing: A Global Approach. *Procedia CIRP* **2015**, *29*, 203–208. [CrossRef]
72. Monticolo, D.; Lahoud, B.E. SemKnow: A Multi-Agent Platform to manage distributed knowledge by using ontologies. In Proceedings of the 2012 IAENG International Conference on Artificial Intelligence and Applications (ICAIA 2012), Hong Kong, China, 14–16 March 2012.
73. Noy, N.; McGuiness, D. *Ontology Development 101: A Guide to Creating Your First Ontology*; Technical Report KSL-01-05 and Stanford Medical Informatics Technical Report SMI-2001-0880; Stanford Knowledge Systems Laboratory: Stanford, CA, USA, 2001.
74. Uschold, M.; King, M. Towards a Methodology for Building Ontologies. In Proceedings of the IJCAI'95 Workshop on Basic Ontological Issues in Knowledge Sharing, Montreal, QC, Canada, 20–25 August 1995; Skuce, D., Ed.; Artificial Intelligence Applications Institute: Edinburgh, UK; pp. 6.1–6.10.
75. Grüninger, M.; Fox, M.S. Methodology for the design and evaluation of ontologies. In Proceedings of the IJCAI'95 Workshop on Basic Ontological Issues in Knowledge Sharing, Montreal, QC, Canada, 20–25 August 1995; Skuce, D., Ed.; Artificial Intelligence Applications Institute: Edinburgh, UK; pp. 6.1–6.10.
76. Fernández-López, M.; Gómez-Pérez, A.; Juristo, N. Methontology: From Ontological Art towards Ontological Engineering. In Proceedings of the Spring Symposium on Ontological Engineering of AAAI, Stanford University, Stanford, CA, USA, 24–26 March 1997; pp. 33–40.
77. Staab, S.; Schnurr, H.P.; Studer, R.; Sure, Y. Knowledge Processes and Ontologies. *IEEE Intell. Syst.* **2001**, *16*, 26–34. [CrossRef]
78. Hacking, T.; Guthrie, P. A framework for clarifying the meaning of triple bottom-line, integrated and sustainability assessment. *Environ. Impact Assess. Rev.* **2008**, *28*, 73–89. [CrossRef]
79. WCDE (World Commission on Environment and Development). *Our Common Future*; Oxford University Press: Oxford, UK, 1987.
80. Uhlman, B.W.; Saling, P. Measuring and communicating sustainability through eco-efficiency analysis. *Chem. Eng. Prog.* **2010**, *106*, 17–26.
81. Brown, K.W.; Kasser, T. Mindful Climate Action: Health and Environmental Co-Benefits from Mindfulness-Based Behavioral Training. *Soc. Indic. Res.* **2005**, *74*, 349. [CrossRef]
82. Norris, K.; Jacobson, S. Content analysis of tropical education programs: Elements of success. *J. Environ. Educ.* **1998**, *30*, 38–44. [CrossRef]
83. Wątróbski, J.; Ziemba, P.; Jankowski, J.; Zioło, M. Green Energy for a Green City—A Multi-Perspective Model Approach. *Sustainability* **2016**, *8*, 702. [CrossRef]
84. Centobelli, P.; Cerchione, R.; Esposito, E. Knowledge Management in Startups: Systematic Literature Review and Future Research Agenda. *Sustainability* **2017**, *9*, 361. [CrossRef]
85. Coldwell, D. Entropic Citizenship Behavior and Sustainability in Urban Organizations: Towards a Theoretical Model. *Entropy* **2016**, *18*, 453. [CrossRef]

86. Carter, R.C.; Rogers, D.S. A framework of sustainable supply chain management: Moving toward new theory. *Int. J. Phys. Distrib. Logist.* **2008**, *38*, 360–387. [CrossRef]
87. Balderjahn, I.; Buerke, A.; Kirchgeorg, M.; Peyer, M.; Seegebarth, B.; Wiedmann, K.P. Consciousness for sustainable consumption: Scale development and new insights in the economic dimension of consumers' sustainability. *AMS Rev.* **2013**, *3*, 181. [CrossRef]
88. Pepper, M.; Jackson, T.; Uzzell, D. An examination of the values that motivate socially conscious and frugal consumer behaviours. *Int. J. Consum. Stud.* **2009**, *33*, 126–136. [CrossRef]
89. Gilg, A.; Barr, S.; Ford, N. Green consumption or sustainable lifestyles? Identifying the sustainable consumer. *Futures* **2005**, *37*, 481–504. [CrossRef]
90. Wackernagel, M.; Yount, J.D. Footprints for sustainability: The next steps. *Environ. Dev. Sustain.* **2000**, *2*, 21–42. [CrossRef]
91. Richomme-Huet, K.; Freyman, J.D. What Sustainable Entrepreneurship Looks Like: An Exploratory Study from a Student Perspective. In Proceedings of the 56th Annual International Council for Small Business (ICSB) World Conference, Stockholm, Sweden, 15–18 June 2011.
92. Husin, S.N.F.S.; Harith, Z.Y.H. The performance of daylight through various type of fenestration in residential building. *Procedia Soc. Behav. Sci.* **2012**, *36*, 196–203. [CrossRef]
93. Kristensen, P. *The DPSIR Framework*; National Environmental Research Institute: Nyborg, Denmark; European Topic Centre, European Environment Agency: Copenhagen, Denmark, 2004.
94. Bialas, A. Computer-aided sensor development focused on security issues. *Sensors* **2016**, *16*, 759. [CrossRef] [PubMed]
95. Medina-Oliva, G.; Voisin, A.; Monnin, M.; Leger, J.B. Predictive diagnosis based on a fleet-wide ontology approach. *Knowl. Based Syst.* **2014**, *68*, 40–57. [CrossRef]
96. Maleki, E.; Belkadi, F.; Ritou, M.; Bernard, A. A Tailored Ontology Supporting Sensor Implementation for the Maintenance of Industrial Machines. *Sensors* **2017**, *17*, 2063. [CrossRef] [PubMed]
97. Gruber, T.R. A Translation Approach to Portable Ontology Specification. *Knowl. Acquis.* **1993**, *5*, 199–220. [CrossRef]
98. Barbau, R.; Krima, S.; Rachuri, S.; Narayanan, A.; Fiorentini, X.; Foufou, S.; Sriram, R.D. OntoSTEP: Enriching product model data using ontologies. *Comput. Aided Des.* **2012**, *44*, 575–590. [CrossRef]
99. Fowler, J.W.; Rose, O. Grand challenges in modelling and simulation of complex manufacturing systems. *Simulation* **2004**, *80*, 469–476. [CrossRef]
100. Musen, M.A. The Protégé project: A look back and a look forward. *AI Matters* **2015**, *1*. [CrossRef] [PubMed]
101. Baader, F.; Calvanese, D.; McGuinness, D.; Nardi, D.; Patel-Schneider, P.F. *The Description Logic Handbook: Theory, Implementation and Applications*; Cambridge University Press: Cambridge, UK, 2003; ISBN 0-521-78176-0.
102. Norris, G.A. Integrating Life Cycle Cost Analysis and LCA. *Int. J. LCA* **2001**, *6*, 118. [CrossRef]
103. Asiedu, Y.; Gu, P. Product life cycle cost analysis: State of the art review. *Int. J. Prod. Res.* **1998**, *36*, 4. [CrossRef]
104. Tsuda, M.; Takaoka, M. Novel evaluation method for social sustainability affected by using ICT services. In Proceedings of the International Life Cycle Assessment & Management Conference, Washington, DC, USA, 4–6 October 2006.
105. Kaiser, F.G.; Wilson, M. Goal-directed conservation behaviour: The specific composition of a general performance. *Personal. Individ. Differ.* **2004**, *36*, 1531–1544. [CrossRef]
106. Gatersleben, B.; Steg, L.; Vlek, C. The measurement and determinants of environmentally significant consumer behavior. *Environ. Behav.* **2002**, *34*, 335–362. [CrossRef]
107. Krstić, B.; Jovanović, S.; Janković-Milić, V. Sustainability Performance Management System of Tourism Enterprises. *Facta Univ.* **2008**, *5*, 123–131.
108. United Nations Division for Sustainable Development (UNDSD). Indicators of Sustainable Development: Guidelines and Methodologies. Available online: http://www.un.org/esa/sustdev/publications/indisd-mg2001.pdf (accessed on 11 July 2017).
109. Hutchins, M.; Sutherland, J. Exploration of measures of social sustainability and their application to supply chain decisions. *J. Clean. Prod.* **2008**, *16*, 1688–1698. [CrossRef]

110. Global Reporting Initiative. *Sustainability Reporting Guidelines: Exposure Draft for Public Comment and Pilot-Testing*; Sustainable Measures: Evaluation and Reporting of Environmental and Social Performance; Greenleaf Publishing in Association with GSE Research: Boston, MA, USA, 1999; Volume 440, No. 474, pp. 440–474.
111. Berger-Schmitt, R.; Noll, H.H. *Conceptual Framework and Structure of a European System of Social Indicators*; EuReporting Working Paper no. 9; Centre for Survey Research and Methodology (ZUMA): Mannheim, Germany, 2000.