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Research article

An ontology-based KBE application for supply chain sustainability assessment

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A R T I C L E I N F O

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A B S T R A C T

Product Lifecycle Management (PLM) plays a key role in digital transformation demanded by Industry 4.0 and life cycle assessment, including sustainability assessment. Knowledge Based Engineering (KBE) applications can support PLM by integrating heterogeneous knowledge from different stages throughout the product life. However, the integration of knowledge from different stages and teams can cause misunderstanding if not represented in a unified form. Furthermore, different forms of knowledge used by different software are neither machine-readable nor human-readable, which also sets obstacles to knowledge integration in KBE applications. Supply chain sustainability assessment is such a scenario that entails integrating knowledge from different sources. This paper firstly implements a sustainability assessment method from other scholar to calculate the supply chain sustainability performance and adapts a sustainability assessment ontology for supply chain sustainability assessment. Then, an example KBE application is developed by implementing the sustainability assessment ontology and calculation method to simulate the knowledge sharing and integration between different teams. Finally, through this example application, it is discussed that the implementation of ontology to represent knowledge in PLM application for collaborative tasks like sustainability assessment can increase the efficiency of data sharing and integration. This paper is a proof of concept for the ontology-based framework. This framework can facilitate to represent knowledge but not create new knowledge, which means it can increase the efficiency of the software development, but cannot provide a better calculation method and assessment framework for supply chain sustainability assessment.

1. Introduction

Product Lifecycle Management (PLM) is to manage the data, processes, business systems, and people in an extended enterprise, which plays a key role in digital transformation demanded by Industry 4.0 (Jaskó et al., 2020) and life cycle assessment (Joshi and Dutta, 2004). PLM software allows to manage the knowledge throughout the entire product lifecycle efficiently and cost-effectively: from ideation, design, and manufacture to service and disposal. Knowledge Based Engineering (KBE) is a technology that can support PLM software development, see details in Section 2. However, there are some challenges to share and integrate the knowledge from different stages of the product:

- Misunderstanding. Different teams have different terminology and convention, which can cause misunderstanding unless expressed in an explicit form. Standardization approach is helpful but not flexible enough due to the complexity and constant-evolving nature of the engineering (Yang et al., 2006).
- Not machine-readable: most applications in specific domain are developed without the prior intent for interoperation and integration with others (Yang and Miao, 2007). Humans need to understand the data and write wrappers to convert it to specific format processable in the domain applications.
- Not human-readable: the data/knowledge in traditional machine-readable data format (SQL database) is not human-readable. If humans want to update or query new data, they have to write program rather than a human-friendly way.

To figure out the above challenges requires a powerful way to store and share knowledge in different phases. Ontology as a semantic way to represent knowledge is seen as a promising candidate to promote sharing and integration (Borsato, 2014). As a kind of graph database, ontology has the advantages of easy extendability and fast-speed query across different databases. Knowledge represented in this form can be queried and processed by machines in order to make data flow more easily between different stages. And it can also be shown and queried in a human-readable way for the related people to maintain the knowledge base, which makes a unified knowledge base practical. A definition of ontology is in Section 2.

Supply chain sustainability assessment (SCSA) is such a scenario that needs to share knowledge between different stages and teams.

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As the importance of sustainable development arises, the sustainability assessment of product supply chain has become an important concern in product lifecycle management. Sustainability assessment is often in relation with the three dimensions: economic growth, environmental protection and social equality. And many studies related to SCSA (Zhang et al., 2005; Kucukvar et al., 2019; Dvaipayana et al., 2021; Yani et al., 2022; Mursidah et al., 2020) show there are also many indicators to be considered in the three dimensions, (e.g. Table 2), which makes the assessment relevant with multi-disciplinary knowledge. However, few of them discuss the difficulties in data sharing and integration from different sources (data collection), which actually is very time-consuming (Kawajiri et al., 2022; Yan et al., 2021).

One of the difficulties in assessing sustainability of supply chain is that the participants of the supply chain have their own scope to assess and optimize, rather than to cooperate with the downstream and upstream. This can lead to some local optimal solutions, rather than the global optimal. There are many deep reasons resulting in this non-cooperation, e.g. technical ones, economical ones, and one of them can be the difficulty of data collection, which is above-mentioned. In the scopes of participants, the data is generated by their own sensors or software system in their own processable formats. But due to the lack of a unified, standardized format, their data can be misunderstood by each others, which means they do not know how to use the data unless they learn on purpose. Considering the data is in raw formats, it can be difficult to learn how to use the data. And even they know the usage of the data after learning, the data still need to be converted into the formats that their own systems can process, which is a time-consuming processing.

In summary, to conduct the assessment entails the exchange of knowledge between different stages and teams. There are some research using ontology in sustainability assessment for some specific domains, e.g., product design (Yang and Song, 2009), enterprise (Muñoz et al., 2013) and urban development (Kuster et al., 2020), which inspire the research question: how to use ontology-based framework to improve the efficiency of the sharing and integrating knowledge across different phases, in order to speed up the development of PLM software for supply chain sustainability assessment.

The aim of this paper is to show the potential of this ontology-based framework in helping the development of PLM software, such as the software components for supply chain sustainability assessment, by sharing and integrating knowledge across different phases of product lifecycle management. It is not to propose a better assessment calculation method and assessment framework for supply chain sustainability assessment. Section 2 introduces the Knowledge Based (KB) approach and ontology to support knowledge representation and integration. Meanwhile, some sustainability assessment research are also presented. Section 3 introduce the sustainability assessment calculation method including the data (Section 3.2) and the adapted ontology (Section 3.3) used as the example in this paper. Then, an example KBE application is developed in Section 4 by implementing the sustainability assessment ontology and calculation method to simulate the knowledge sharing between different teams. Finally, Section 5 discusses how ontology helps to share and integrate the knowledge in PLM software, together with the contribution to supply chain sustainability assessment, and also the scope of this ontology-based framework. The abbreviations used in the paper are explained in Table 1.

Table 1
List of abbreviation used in the paper.

Abbreviation	Explanation
PLM	Product Lifecycle Management
SQL	Structured Query Language
KB	Knowledge-Based, Knowledge Base
KBS	Knowledge Based System
KBE	Knowledge Based Engineering
POP	Procedure-Oriented Programming
OOP	Object-Oriented Programming
OO	Object-Oriented
FCE	Fuzzy Comprehensive Evaluation
SPARQL	SPARQL Protocol and RDF Query Language
GUI	Graphic User Interface
SCSA	Supply Chain Sustainability Assessment

2. Research background

2.1. KBE and ontology

Knowledge Based Engineering System is the merger of the terms "Knowledge Based System (KBS)" and "Engineering", while Knowledge Based Engineering (KBE) is the technology based on the use of these systems (La Rocca, 2012), which means the implementation of KBS in engineering domain. The name of KBE may be ambiguous, as it seems to indicate the existence of the engineering that is not based on knowledge. Actually, the term "knowledge" refers to rules, hence this name is highlighting that the Knowledge-Based (KB) approach focuses on the reuse of engineering rules (knowledge) by knowledge management techniques, e.g., capture, formalization, representation and integration. To make an analogy, the conventional approach is like Procedure-Oriented Programming (POP), which focuses more on problem-solving procedures. While KB approach is like Object-Oriented Programming (OOP), which solves problems by defining the well-described objects from the captured knowledge with reuse purpose. La Rocca (2012) gives an extended definition of KBE:

Knowledge based engineering (KBE) is a technology based on the use of dedicated software tools called KBE systems, which are able to capture and systematically reuse product and process engineering knowledge, with the final goal of reducing time and costs of product development by means of the following:

1. Automation of repetitive and non-creative design tasks;

2. Support of multidisciplinary design optimization in all the phases of the design process.

Knowledge Based System (KBS) are computer applications that use the KB approach to solve problems in a specific domain. It evolves from two types of Artificial Intelligence (AI) systems: the rule based systems (RBSs) and frame based systems (FBSs). The previous one is based on the well-known IF-THEN expert system, while the latter one is based on Object-Oriented (OO) knowledge representation, which is a closer ancestor of KBS (Negnevitsky, 2005). Compared with the non-KB approach, KBS solves problems by reasoning about facts. KBE adapts KBS towards the specific needs of the engineering design domain by enhancing the *geometry manipulation* and *data processing* (La Rocca, 2012). Parameterization is a key feature of KBE to represent the product knowledge in the OO approach. Ref. Zhang et al. (2021) demonstrates the ability of KBE to realize the geometry manipulation and data processing. This paper focuses on the data processing aspect of KBE application.

Ontology is a technology for knowledge representation, which is an important component of KBS. According to Gruber (1993) and Studer et al. (1998), an ontology is a formal, explicit specification of a shared conceptualization. The term "conceptualisation" refers to the abstract model of some phenomenon by extracting the relevant information from the real-world phenomenon containing infinite information. The term "formal" indicates that the representation should be in some sort of well understood logic to make itself machine-readable (Studer et al., 1998; Mika and Akkermans, 2003). "Explicit" refers to the fact that the type of concepts used, and the constraints on their use are explicitly defined (Studer et al., 1998), which means the relations and attributes related to the objects are pre-defined. While the term "shared" reflects that the knowledge captured in the ontology is accepted by the related community rather than private to some individuals (Studer et al., 1998;

Mika and Akkermans, 2003; Yang et al., 2019). Roughly speaking, ontology works as a more flexible data schema regulating how the data should be organized, which makes the ontology-based application easier to extend and integrate data from different sources.

2.2. Sustainability performance assessment

According to the United Nations report (Brundtland, 1987), sustainability is to meet the needs of the present without compromising the ability of future generations to meet their own needs. As introduced, the sustainability assessment of a supply chain requires the data from multi-disciplinary domains, which is a typical scenario for team collaboration. There are already some research implementing ontology to assess the sustainability performance for some specific domains. Muñoz et al. (2013) develops an ontological framework for the environmental sustainability assessment of the enterprise. In this work, the ontology, as the technology for knowledge sharing, provides an enterprise decision-making supporting tool by combining different information systems associated with the enterprise functions. Kuster et al. (2020) reconciles several domain-specific ontologies within one high-level ontology called the Urban District Sustainability Assessment (UDSA) ontology, which can support the creation of real-time urban sustainability assessment software. From these works, it can be seen that ontology is a powerful tool to share and integrate the sustainability knowledge. However, few study implements ontology-based framework in SCSA.

Regarding the supply chain sustainability assessment, Zhang et al. (2005) provide an easy-to-use calculation method based on fuzzy comprehensive evaluation (FCE) method. This method can take the uncertainty of the assess dimensions into account, expanding the amount of information and increasing the credibility of conclusion. Kucukvar et al. (2019) develop 14 macro level indicators to assess the supply chain of food consumption in the US. Dvaipayana et al. (2021) design a sustainable supply chain performance monitoring system considering 20 indicators from financial, internal business process and learning & growth perspectives. Yani et al. (2022) propose 24 indicators from economic, social, environmental and resource aspects for sustainability assessment of sugarcane agroindustry supply chain. Mursidah et al. (2020) also develop a model for SCSA of sugarcane agroindustry concerning 20 indicators using Artificial Neural Network (ANN) and Decision Tree. Meanwhile, there are some research (Yang and Song, 2009; Konys, 2018; Stark and Pförtner, 2015) providing the ontologies for sustainable product design to integrate the knowledge from different sources, which can be adapted to be used in KBE application for supply chain sustainability assessment.

3. The knowledge modeling

3.1. Overview

A KBE application can reuse the captured knowledge to conduct the supply chain sustainability assessment (SCSA) without manual intervention. An important step to develop a KBE application is to capture and formalize the knowledge for reuse purpose, and then represent it in proper format, e.g. ontology. As this paper is to demonstrate the potential of ontology-based framework in SCSA, rather than to propose a better calculation method and assessment framework for SCSA, the selection of the calculation method and the assessment framework is not a key concern in this paper.

This paper uses the ready sustainability assessment knowledge (the calculation method and the assessment framework) from other studies. As it is for demonstration purpose, the criteria to select are:

- The calculation method is simple, the input and output are clear, and better with example data.
- The calculation method covers various professional domains, reflecting the various data sources and the heavy workload of data conversion.
- The assessment framework is simple and compatible to the selected calculation method.

Table 2
The factors and indexes for supply chain sustainability assessment.
Source: Adapted from Ref. Zhang et al. (2005).

Factor	Factor index
Finance value	Return on assets (ROA) Cash turnover ratio (CTR) Profit growth rate (PGR) Yield of net asset (YNA)
Environmental protection	Environmental protection efficiency (EPE) Materials utilization ratio (MUR) Energy utilization ratio (EUR) Environmental impact indicator(EII)
Information value	Information sharing ratio (ISR) Information flow rate (IFR) Information utilization ratio (IUR) Information inefficiency ratio (IIR)
Customer service	Customer lost rate (CLR) Customer satisfaction ratio (CSR) Customer valuable ratio (CVR)
Cost	Human resource cost (HRC) Materials flow cost (MFC) Information cost(IC) Asset cost (AC)
Operation flexibility	Order cycle time (OCT) Products flexibility (PF) Service response speed (SRS) Delivery flexibility (DF) Amount flexibility (AF)

Based on the above-listed criteria, the method and data from Ref. Zhang et al. (2005) is selected. And an ontology from Ref. Yang and Song (2009) is adapted and reused to represent the sustainability assessment framework, i.e. to define the sustainability assessment options. Regarding other calculation methods and the assessment frameworks, as long as they can be expressed in an explicit form, they can be programmed as the components of the KBE application. Specifically, the calculation methods can be expressed as functions to be called by the KBE application. And the assessment framework can be expressed as ontology to be shared with other teams and to formalize their data in a unified format.

3.2. A sustainability assessment method for supply chain and the data as example

Once again, as the aim of this paper is not to study assessment method, the method and data from Ref. Zhang et al. (2005) are used for simplification purpose. The two-layer FCE method is implemented as the example method to integrate the different data sources for sustainability assessment. The short method introduction is as following:

1. Establish the assessment factors set U.
   The paper uses the factors from Ref. Zhang et al. (2005): finance value, environmental protection, information value, customer service, cost, and operation flexibility. And specific indexes are chosen for each factor as the second layer (Table 2).
2. Establish the five-level assessment comments set V.

$$V = \left\{ excellent, \quad better, \quad good, \quad general, \quad bad \right\}. \tag{1}$$

3. Establish the fuzzy assessment matrix R_i for each factor class.

R_1 as an example is

$$R_1 = \begin{bmatrix} 0.565 & 0.325 & 0.085 & 0.035 & 0 \\ 0.105 & 0.382 & 0.273 & 0.112 & 0.128 \\ 0 & 0.115 & 0.156 & 0.456 & 0.273 \\ 0.426 & 0.315 & 0.164 & 0.095 & 0 \end{bmatrix}. \quad (2)$$

Each row in the matrix represents the membership degree distribution. The data in Eq. (2) is from Ref. Zhang et al. (2005) for simplification purpose, other matrixes (R_2 to R_6) are omitted to shorten the length. A detailed calculation introduction explains that each element is obtained by the classical ridge distribution calculation and normalization (Zhang and Feng, 2018). In some simple cases, these matrixes can be obtained by expert questionnaires.

4. Establish the weight vector for each factor and index.
The weight vector for factor is

$$W = [0.182, 0.225, 0.115, 0.165, 0.142, 0.171]. \quad (3)$$

And the weight vectors of each index set are:

$$\begin{aligned} W_1 &= [0.275, 0.225, 0.216, 0.284] \\ W_2 &= [0.235, 0.265, 0.274, 0.226] \\ W_3 &= [0.260, 0.260, 0.240, 0.240] \\ W_4 &= [0.328, 0.412, 0.260] \\ W_5 &= [0.230, 0.290, 0.250, 0.230] \\ W_6 &= [0.230, 0.175, 0.210, 0.200, 0.185] \end{aligned} . \quad (4)$$

5. Calculate synthetical assessment matrix of single factor class.
Considering the weight vector for each index, the fuzzy matrix of synthetical assessment can be obtained:

$$B = \begin{bmatrix} W_1 \bullet R_1 \\ W_2 \bullet R_2 \\ W_3 \bullet R_3 \\ W_4 \bullet R_4 \\ W_5 \bullet R_5 \\ W_6 \bullet R_6 \end{bmatrix} = \begin{bmatrix} 0.299 & 0.289 & 0.165 & 0.160 & 0.087 \\ 0.045 & 0.115 & 0.248 & 0.394 & 0.198 \\ 0.118 & 0.199 & 0.394 & 0.182 & 0.107 \\ 0.152 & 0.294 & 0.250 & 0.207 & 0.097 \\ 0.160 & 0.333 & 0.283 & 0.174 & 0.050 \\ 0.164 & 0.284 & 0.298 & 0.172 & 0.082 \end{bmatrix}. \quad (5)$$

6. Calculate synthetical assessment of supply chain performance.
Based on fuzzy assessment method, three fuzzy operators, i.e. $M(\wedge, \vee)$, $M(power, \wedge)$, $M(\cdot, +)$, are adopted to avoid unilateralism of the assessment. The three operators are introduced:

- $M(\wedge, \vee)$ operator: first take the minimum and then maximum.

$$W \circ B = [\vee_{i=1}^{m}(w_i \wedge b_{i1}), \quad \vee_{i=1}^{m}(w_i \wedge b_{i2}), \ldots, \vee_{i=1}^{m}(w_i \wedge b_{iP})], \quad (6)$$

where $\vee_{i=1}^{m}(w_i \wedge b_{iP}) = max_{i=1}^{m}(min(w_i, b_{iP}))$, m is the row number of the matrix B, P is the dimension of the assessment comments set V.

- $M(power, \wedge)$ operator: first take the power and then minimum.

$$W * B = [\wedge_{i=1}^{m}(b_{i1}^{w_i}), \wedge_{i=1}^{m}(b_{i2}^{w_i}), \ldots, \wedge_{i=1}^{m}(b_{iP}^{w_i})]. \quad (7)$$

- $M(\cdot, +)$ operator: first take the product and then sum.

$$W \bullet B = \left[\sum_{i=1}^{m} w_i \cdot b_{i1}, \sum_{i=1}^{m} w_i \cdot b_{i2}, \ldots, \sum_{i=1}^{m} w_i \cdot b_{iP}\right]. \quad (8)$$

Based on the fuzzy operators, the synthetical assessment matrix is obtained:

$$\tilde{B} = \begin{bmatrix} W \circ B \\ W * B \\ W \bullet B \end{bmatrix} = \begin{bmatrix} 0.182 & 0.182 & 0.225 & 0.225 & 0.198 \\ 0.478 & 0.615 & 0.720 & 0.716 & 0.652 \\ 0.154 & 0.246 & 0.264 & 0.227 & 0.110 \end{bmatrix}. \quad (9)$$

Taking weight vector $\tilde{W} = [1/3, 1/3, 1/3]$, the assessment result is obtained:

$$\tilde{S} = \tilde{W} \bullet \tilde{B} = [0.271, 0.348, 0.403, 0.389, 0.32]. \quad (10)$$

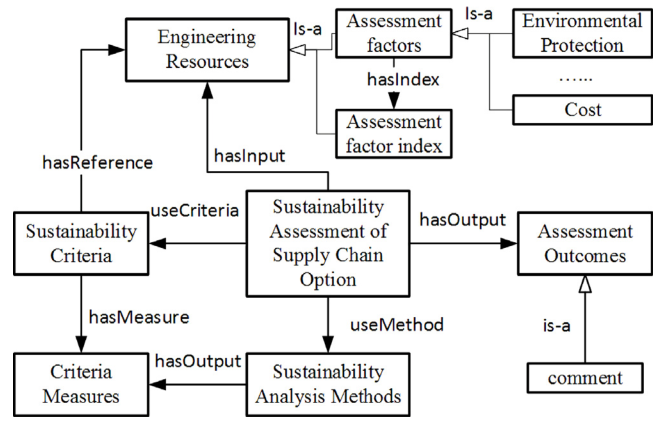

Fig. 1. The ontology about sustainability assessment framework.
Source: Adapted from Ref. Yang and Song (2009).

7. Define a score vector $G = [100, 80, 60, 30, 10]$ corresponding to the assessment comment set V, and normalize the assessment result ($\tilde{S}$) to get the normalized assessment vector

$$\tilde{S}_n = [0.156, 0.201, 0.233, 0.225, 0.185]. \quad (11)$$

Then the score of the whole supply chain performance assessment is $S = G \bullet \tilde{S}_n = 54.54$.

3.3. A sustainability assessment ontology for supply chain

As introduced in the above, the ontology representing the sustainability assessment knowledge, as the model of data, can help to remove the ambiguity of multi-disciplinary knowledge and increase the extensibility and interoperability of the application. Therefore, an ontology adapted from Ref. Yang and Song (2009) is reused to define the sustainability assessment options, as illustrated in Fig. 1. This ontology consists of engineering resource, sustainability criteria, criteria measures, sustainability analysis methods and assessment outcomes, which means:

- Engineering resources: the factors considered in sustainability assessment, including finance, environment, logistic and etc.
- Sustainability criteria: the chosen criteria to judge from the criteria measures if the supply chain is good or not.
- Criteria measures: the score calculated by the method in Section 3.2.
- Sustainability analysis methods: the information on the calculation method, e.g., name, input, output.
- Assessment outcomes: the conclusion comment on the sustainability performance of the supply chain.

Fig. 2 elaborates an example of two sustainability assessment factors and an index with the attributes. Among the six assessment factors, "environmental_protection" and "cost" are expanded as examples, connected by the relation "hasIndex" with the corresponding indexes. And one index named "Materials_utilization_ratio_MUR" is instantiated with the example value as the attributes. In this way, all the data needed in the calculation can be stored in the ontology.

When the sustainability assessment for a supply chain is needed, the application first query and parse "sustainability assessment of supply chain option" related to this supply chain. Then the application read the "Sustainability analysis methods" object and call the calculation function pointed to by this object. This calculation function will retrieve the needed data including the membership degree, the weight vector and etc., execute the calculation, and store the result into "Criteria measures". Then the application compares the "Criteria measures" and

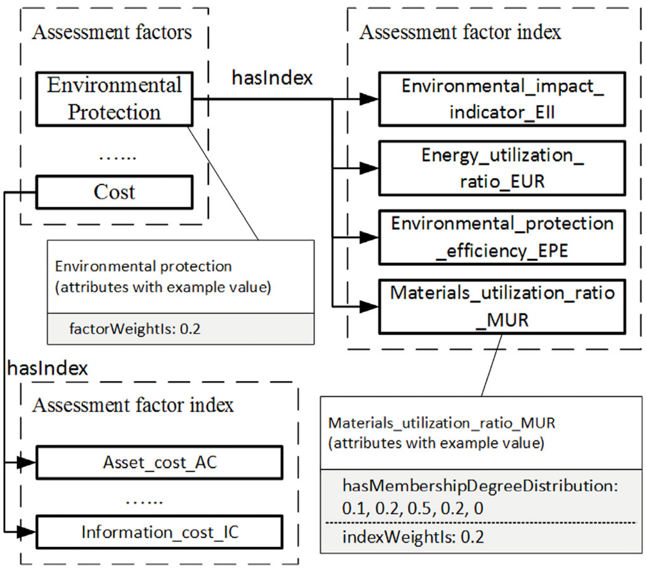

Fig. 2. The assessment factor example.

"Sustainability criteria", and gives the "Assessment outcomes", i.e. the "comment" in this paper.

After the assessment, all the related data will be updated to the ontology stored in the knowledge base. If other teams need the assessment comment, they can retrieve the comment through query language, and use the data in their environment. If the sustainability assessment team wants to apply a new calculation method, they can add the related information into the corresponding objects and write the new functions to work with the newly added data. And for the other teams, what they need is still the query language to retrieve the data they need, rather than to analyze and parse a new data file to extract the needed data. This is a case showing how ontology helps to promote the extendability and interoperability of the application.

4. The KBE application

4.1. The application introduction

In order to demonstrate how to use ontology-based framework to improve the efficiency of the sharing and integrating knowledge across different phases of SCSA, this paper proposes a simple case evaluating the sustainability performance for a supply chain with KBE application. This case is to develop a KBE application based on the predefined sustainability assessment ontology for supply chain, with the FCE method as the calculation method to evaluate a supply chain.

This KBE application captures and formalizes the knowledge used in SCSA, which is shared with other teams. Thus the data from different sources can be integrated in a high-efficient way, and the supply chain sustainability assessment (SCSA) can be conducted without much manual intervention, which reduces the human labor and promotes the digitization level. Additionally, as the application is in ontology-based KBE framework, it is relatively easy to extend and interoperate with other applications, which also speeds up the development of PLM software for SCSA.

The architecture of the KBE application is illustrated in Fig. 3. The sustainability assessment team determines the assessment options and defines the knowledge in the ontology format. Then they share the ontology with other related teams and inform them to input the assessment needed knowledge of their domains into the knowledge base. Due to the benefits brought by ontology, they can understand what the sustainability assessment team needs and give the right input into the knowledge base (with their ontology_updater or in SPARQL

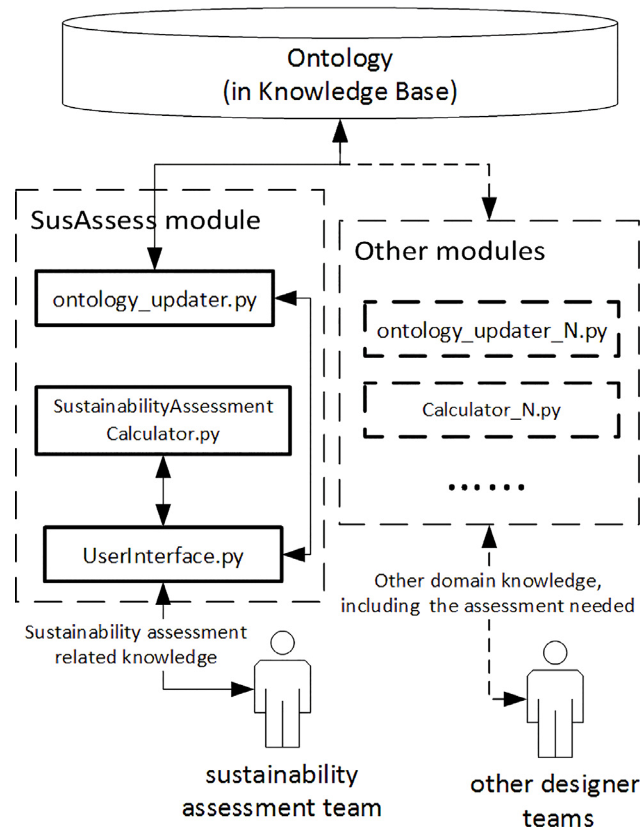

Fig. 3. The KBE application architecture.

language). After all the data (or knowledge) is collected into the knowledge base, the sustainability assessment team can type command in UserInterface.py to retrieve the needed knowledge without misunderstanding (by ontology_updater.py), and then conduct the assessment (by SustainabilityAssessmentCalculation.py) and update the result into the knowledge base (by ontology_updater.py). With this application, different teams can work together to compare several supply chains to choose the one with better sustainability performance. The modules in the architecture are described as following:

- ontology_updater.py: to query and update the knowledge in the knowledge base using SPARQL language.
- SustainabilityAssessmentCalculation.py: to calculate the sustainability performance score and give the conclusion.
- UserInterface.py: to receive the user input, call other modules and show the assessment result.

4.2. The demonstration

When the assessment needed knowledge is ready in the knowledge base, the sustainability assessment team can use the application to evaluate the supply chains automatically and update the assessment result to the unified knowledge base. They input the name of the supply chain and see the assessment result.

The process is demonstrated in Fig. 4. Fig. 4(a) gives an example how another expert team inputs their data into the knowledge base, i.e., the cost evaluation team is inputting the membership degree vector (0.565, 0.325, …, 0) into the knowledge base in SPARQL language. Similarly, other teams, e.g. finance team, environment team and etc., can input their data in the same way. If needed, the KBE development team can also make a Graphic User Interface (GUI) for other teams to input data. Fig. 4(b) shows that the calculation module gives the

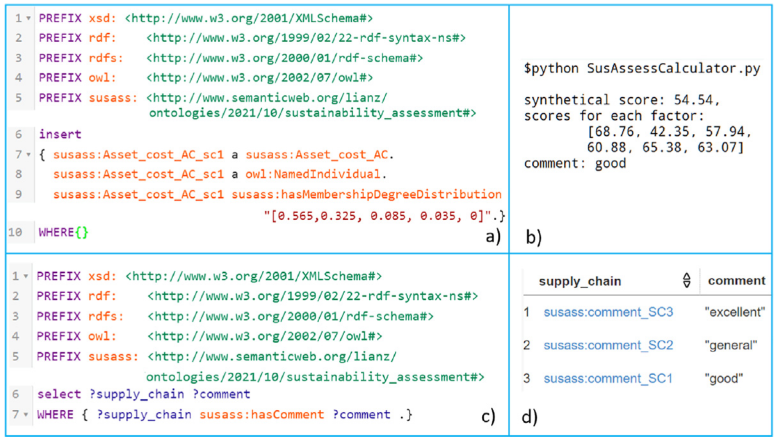

Fig. 4. The demonstration of the KBE application. (a) Different teams input their data into the unified knowledge base. (b) The calculation process. (c) The query to get the assessment result. (d) The assessment results of different supply chains.

assessment result after receiving all the needed data. After the calculation is done, the ontology updater module will send the result into the knowledge base, which is not shown in the figure. Fig. 4(c) illustrates that the sustainability assessment team queries the sustainability performance (the comment) of every supply chain in SPARQL language. This function can also be hard-coded into the Python script. Fig. 4(d) shows the list returned by the query, which shows the assessment outcomes for several supply chains. With this tool, the sustainability assessment team can conduct this collaborative task high-efficiently, then provide reference to support the decision-making related to supply chain optimization.

5. Discussion

The sustainability assessment ontology represents the related knowledge in an explicit form, which reduces the misunderstanding between different teams and helps to share and integrate knowledge across different stages. Furthermore, the extendability of ontology makes it practical to store knowledge in a unified database (knowledge base), which promotes the interoperability of different software applications.

Fig. 5 shows the different collaboration patterns. In conventional pattern, different teams have their own software systems generating the data files in different formats. If a team needs the data from different teams, they need to understand the data files rightly and write wrappers to parse the data and convert it into the format processable in their own systems, which is a low efficiency way. During this process, they can misunderstand the knowledge from different domains, as the data files are not designed to be shared with other software. When the system becomes large, to write wrappers for many data files can be time-consuming, not mention the chaos brought by the change of data formats.

The ontology-based knowledge base is a good way to figure this out. It provides an extendable format to represent the knowledge from different domains, which makes a unified representation possible. With this unified knowledge representation, data is explicitly explained, reducing the chance to misunderstand the multi-disciplinary data. And as no need to write the wrappers, the time in integrating the knowledge from different domains is shortened significantly.

Considering the data in Table 2, these data come from different sources, and in different formats. In conventional way, the assessment team need to communicate with other teams to study the usage of the data, and then write the wrappers to convert the data. This can be a heavy workload when there are many data sources and formats. With the help of ontology-based knowledge base, each team uploads the data in the format regulated in ontology, which is equivalent to that the data is converted before upload and other people do not need to convert any more.

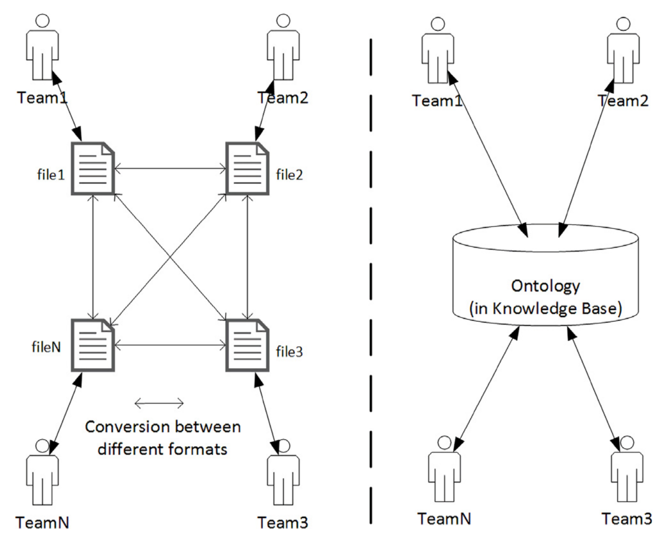

Fig. 5. The conventional v.s. ontology-based.

The ontology-based knowledge representation facilitates the multi-disciplinary knowledge sharing and integration, simplifying the PLM software development, promoting the digital transformation and design automation. A high-level automation means high efficiency and less human labor needed. Less labor cost expense can increase the profit rate, which is helpful to the sustainable development of the companies. Furthermore, this can also reduce the burden of the sustainability assessment team, which can make sustainability assessment a widely used process in companies.

With the help of a high efficiency tool, the sustainability performance can be assessed automatically. The assessment result can provide reference to improve the sustainability performance of the supply chain. With a more sustainable supply chain, the companies are contributing to the environment, which is also advocated by the UN sustainable development goal (SDG) 12.2 that "By 2030, achieve the sustainable management and efficient use of natural resources" (United Nations, 2021).

Meanwhile, it is worth noticing that this paper is a proof of concept for the ontology-based framework. It shows that the ontology-based framework can facilitate to represent knowledge but not create new knowledge. In other words, it can increase the efficiency of the software development, but cannot provide a better calculation method and assessment framework for SCSA.

6. Conclusions

This paper provides an example KBE application to assess supply chain sustainability performance, which is based on the reuse of a ready calculation and ontology-based knowledge representation. The ontology-based knowledge representation can simplify the PLM software development by facilitating the multi-disciplinary knowledge sharing and integration in collaborative tasks like sustainability assessment. From this example application, some conclusions can be drawn.

- Ontology-based knowledge representation can provide a unified and flexible data format for the teams in collaboration, which can reduce the misunderstanding caused by various data formats.
- Ontology-based knowledge representation with SPARQL query language makes the data exchange more human-readable than the conventional data exchange patterns.
- A unified and flexible data format makes a unified knowledge base possible.
- A unified knowledge base can reduce the time spent on writing data wrappers, which increases the efficiency of software development.
- The efficiency of SCSA itself can also be improved with a software, leading to a more sustainable supply chain, and also contributing to achieve the sustainable management and efficient use of natural resources.

In the future work, a larger scale of knowledge integration can be investigated to cover more stages of product lifecycle management, aiming at integrating more data sources and digitalizing more knowledge to provide more automation in PLM. Additionally, some more adaptive tools based on ontology-based knowledge representation need to be studied to manipulate the knowledge in the changeable formats, in order to improve the efficiency of capturing and formalizing the knowledge by providing more user-friendly experience.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Liang Zhang reports a relationship with Norwegian University of Science and Technology that includes: employment. Anna Olsen reports a relationship with Norwegian University of Science and Technology that includes: employment. Andrei Lobov reports a relationship with Norwegian University of Science and Technology that includes: employment.

References

Borsato, M., 2014. Bridging the gap between product lifecycle management and sustainability in manufacturing through ontology building. Comput. Ind. 65 (2), 258–269.

Brundtland, G.H., 1987. Report of the World Commission on Environment and Development: "Our Common Future". UN.

Dvaipayana, M.A.T., Ridwan, A.Y., Santosa, B., 2021. Design of sustainable supply chain performance monitoring system for construction material management: Sustainable balanced scorecard–SCOR–ISO 14001 model. In: 2021 International Conference Advancement in Data Science, e-Learning and Information Systems (ICADEIS). IEEE, pp. 1–6.

Gruber, T.R., 1993. A translation approach to portable ontology specifications. Knowl. Acquis. 5 (2), 199–220.

Jaskó, S., Skrop, A., Holczinger, T., Chován, T., Abonyi, J., 2020. Development of manufacturing execution systems in accordance with industry 4.0 requirements: A review of standard-and ontology-based methodologies and tools. Comput. Ind. 123, 103300.

Joshi, N., Dutta, D., 2004. Enhanced life cycle assessment under the PLM framework. In: Proceeding of the International Intelligent Manufacturing Systems Forum. pp. 17–19.

Kawajiri, K., Tahara, K., Uemiya, S., 2022. Lifecycle assessment of critical material substitution: Indium tin oxide and aluminum zinc oxide in transparent electrodes. Resour. Environ. Sustain. 100047.

Konys, A., 2018. An ontology-based knowledge modelling for a sustainability assessment domain. Sustainability 10 (2), 300.

Kucukvar, M., Ismaen, R., Onat, N.C., Al-Hajri, A., Al-Yafay, H., Al-Darwish, A., 2019. Exploring the social, economic and environmental footprint of food consumption: a supply chain-linked sustainability assessment. In: 2019 IEEE 6th International Conference on Industrial Engineering and Applications (ICIEA). IEEE, pp. 733–742.

Kuster, C., Hippolyte, J.-L., Rezgui, Y., 2020. The UDSA ontology: An ontology to support real time urban sustainability assessment. Adv. Eng. Softw. 140, 102731.

La Rocca, G., 2012. Knowledge based engineering: Between AI and CAD. Review of a language based technology to support engineering design. Adv. Eng. Inform. 26 (2), 159–179.

Mika, P., Akkermans, H., 2003. Analysis of the State-of-the-Art in Ontology-Based Knowledge Management. Tech. Rep., Vrije Universiteit, Amsterdam.

Muñoz, E., Capón-García, E., Laínez, J.M., Espuña, A., Puigjaner, L., 2013. Considering environmental assessment in an ontological framework for enterprise sustainability. J. Cleaner Prod. 47, 149–164.

Mursidah, S., Djatna, T., Fauzi, A.M., et al., 2020. Supply chain sustainability assessment system based on supervised machine learning techniques: The case for sugarcane agroindustry. In: 2020 International Conference on Computer Science and its Application in Agriculture (ICOSICA). IEEE, pp. 1–7.

Negnevitsky, M., 2005. Artificial Intelligence: A Guide to Intelligent Systems. Pearson education.

Stark, R., Pförtner, A., 2015. Integrating ontology into PLM-tools to improve sustainable product development. CIRP Ann. 64 (1), 157–160.

Studer, R., Benjamins, V.R., Fensel, D., 1998. Knowledge engineering: Principles and methods. Data Knowl. Eng. 25 (1–2), 161–197.

United Nations, 2021. Sustainable development goal 12. URL: https://sdgs.un.org/goals/goal12 [Online; accessed 29-December-2021].

Yan, K., Xu, J.-c., Gao, W., Li, M.-j., Yuan, Z.-w., Zhang, F.-s., Elser, J., 2021. Human perturbation on phosphorus cycles in one of China's most eutrophicated lakes. Resour. Environ. Sustain. 4, 100026.

Yang, L., Cormican, K., Yu, M., 2019. Ontology-based systems engineering: A state-of-the-art review. Comput. Ind. 111, 148–171.

Yang, Q., Miao, C., 2007. Semantic enhancement and ontology for interoperability of design information systems. In: 2007 IEEE Conference on Emerging Technologies and Factory Automation (EFTA 2007). IEEE, pp. 169–176.

Yang, Q., Miao, C., Zhang, Y., Gay, R., 2006. Ontology modelling and engineering for product development process description and integration. In: 2006 4th IEEE International Conference on Industrial Informatics. IEEE, pp. 85–90.

Yang, Q., Song, B., 2009. Semantic knowledge management to support sustainable product design. In: 2009 International Association of Computer Science and Information Technology-Spring Conference. IEEE, pp. 419–423.

Yani, M., Asrol, M., Hambali, E., Papilo, P., Mursidah, S., Marimin, M., et al., 2022. An adaptive fuzzy multi-criteria model for sustainability assessment of sugarcane agroindustry supply chain. IEEE Access 10, 5497–5517.

Zhang, L., Berisha, B., Lobov, A., 2021. A parametric model of umbilical cable with siemens NX considering its reliability. IFAC-PapersOnLine 54 (1), 187–192.

Zhang, P., Feng, G., 2018. Application of fuzzy comprehensive evaluation to evaluate the effect of water flooding development. J. Pet. Explor. Prod. Technol. 8 (4), 1455–1463.

Zhang, H.C., et al., 2005. Study on the performance assessment of green supply chain. In: 2005 IEEE International Conference on Systems, Man and Cybernetics, Vol. 1. IEEE, pp. 942–947.