Knowledge Structuring Tool for Sustainability Science Based on Ontology Engineering

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Abstract

In Sustainability Science (SS) it is not only difficult to identify what needs to be solved but how to solve the problems once identified. There has been no consensus on underlying question of "What is structuring in SS?" This paper focuses on articulating in the form of a reference model a set of required elements, functions, and actions for structuring SS knowledge and on realizing a part of that reference model by developing a prototype knowledge system for mapping relevant concepts and their linkages in SS. First, we develop a reference model composed of five layers. Second, we develop an ontology-based mapping tool as a tentative solution at Layer 2 of the reference model. Third, we assess whether the developed tool is compliant with the reference model for SS. This study concluded that the developed tool can facilitate divergent exploration, the function of Layer 2.

1. Introduction

Establishing a new scientific base is necessary to cope with impending problems concerning a long-term global sustainability. The emerging field of "sustainability science" (SS) is a representative and ambitious attempt at building a new discipline in this context. Komiyama and Takeuchi (2006) define SS as "comprehensive, holistic approach to identification of problems and perspectives involving the sustainability of global, social, and human systems.

Given this definition of SS, it is still difficult to answer *what* we should identify as problems and *how* we should solve them in the context of this emerging discipline. In the initial phase of establishing a new discipline, a lack of a clear and shared understanding of "what to solve" and "how to solve" is not unusual, but this background is not yet clear enough to assemble various disciplines into SS.

In pursuing SS, we must construct a knowledge platform that "enables us to replace the current piecemeal approach with one that can develop and apply comprehensive solutions to these problems" (Komiyama and Takeuchi 2006). Such comprehensiveness can be attained by systematic reorganization of disparate existing fields. Thus, structuring knowledge is itself an important task for SS, which usually treats complex and evolving problems. In addition, sharing explicitly structured knowledge about SS among scientists from various disciplines is crucial to facilitating collaboration for interdisciplinary SS, but SS researchers are not sure what they want to look for by structuring knowledge in SS, nor do they share a common understanding of what is required in order to achieve the structuring of knowledge.

However, we cannot meet the challenges of "what to solve" and "how to solve" only by structuring knowledge. Knowledge structuring must include the support of thinking processes. Existing SS systems are not designed adequately for SS needs because those systems are mainly static structures representing SS and have no link to tools for supporting problem finding and solving.

In order to overcome this situation we need to develop a knowledge system for SS which realizes dynamic structuring coupled with human thinking and without depending on a specific domain. This paper focuses on articulating in the form of a reference model a set of required elements, functions, and actions for structuring SS knowledge. The paper then realizes a part of that reference model by developing a prototype knowledge system for mapping relevant concepts and their linkages in SS. In section 2, we propose a five-layer reference model as a development roadmap for structuring knowledge in SS. In section 3, we develop an ontology-based knowledge system and mapping tool to clarify multi-perspective conceptual chains. In section 4, we examine the tool's conformity to the proposed reference model and discuss its contribution to reframing user's knowledge landscape.

2. Reference Model for Knowledge Structuring in SS

2.1. Challenges of Knowledge Structuring in SS

Clark (2007) stated that SS should be defined not by the domains it covers but by the problems it tackles.

Several types of issues are addressed in SS. First, there are issues including global warming that require researchers to simultaneously understand phenomena and solve problems even though the whole mechanism is unclear. Second, there are issues that require the "precautionary principle", such as natural disasters and infections in relation to escalating uncertainty caused by climate change. Third, there are issues including use of food crops as biofuels that require the simultaneous advance of knowledge and problems. Fourth, there are issues including destruction of tropical rainforest that require the trade-off between global and local problem-solving. Therefore, sustainability issues are multiple, multilayered and exploratory.

These properties of sustainability issues require that a knowledge system for SS implements dynamic structuring.

2.2. Developing a Reference Model

We propose a reference model[1] that consists of layers corresponding to five kinds of information: raw data, underlying static information structure, dynamic information reflecting individual perspectives, dynamic information organizing perspectives within context, and methodological information. The reference model is not a solution for structuring knowledge; rather it is a model that can be referred to when discussing knowledge structuring in SS. It contributes to evaluating and understanding the differences and commonalities of knowledge structuring tools and methods to be proposed in the future by providing a common framework in which they are compared. Hess and Schieder have verified the conformity between reference models and their domain models on a specific domain (Hess and Schlieder 2006).

As shown in Fig. 1, the reference consists of five layers. The bottom layer, Layer 0, is the data layer and stores raw data corresponding to the real world. Layer 1, the ontology layer, stores the ontology for explaining and understanding the raw data at Layer 0. The ontology describes the concepts and relationships related to SS that exist in the real world. Another function of the ontology is to provide a common terminology for promoting mutual understanding across domains. Typical tasks performed at Layer 1 include metadata generation for virtual organization of the raw data and efficient retrieval of the raw data using the metadata.

Layer 2 handles dynamic information that reflects individual perspectives. The main task supported by this layer is the divergent exploration of the conceptual world realized at Layer 1, which systematizes the concepts appearing in the SS world. Divergent exploration in "an ocean of concepts" uses divergent thinking across domains to guide researchers searching for interesting concepts/relationships that have been hidden in the conventional unstructured world. Divergent exploration can be performed by obtaining what we call "multi-perspective conceptual chains" through selection of arbitrary concepts according to the explorer's intention.

After referring proposed conceptual chains, the explorer would move on to a convergent thinking stage at Layer 3. The task of this layer is "context-based convergent thinking." At this layer the explorer can set a specific context of a problem that he or she actually treats and obtain "multiple convergent conceptual chains" (Klein 2004) in accordance with the given context.

At Layer 4, using all the information and knowledge obtained at the sublayers, the explorer will pursue essential problem-solving tasks such as setting the conditions for solving a problem or searching for a new problem, as well as information integration, innovation and abduction.

While the bottom two layers are static, the top three layers are dynamic. The information in the top layers is dynamically generated as required by the tasks at those layers. This dynamism is one of the important characteristics of the reference model.

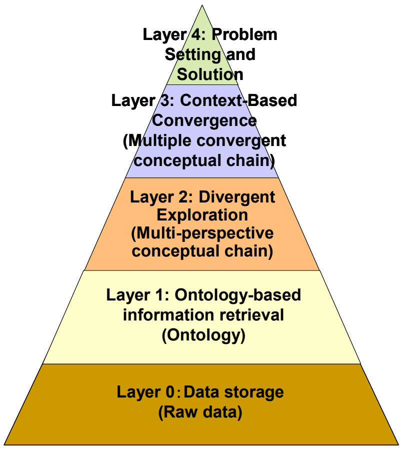

Fig. 1 Layered structure of the reference model.

3. Structuring SS with Ontology Engineering Technology

3.1 Ontology-based Information Retrieval

At Layer 1, we constructed SS ontology using an ontology development tool named Hozo[2], which is based on fundamental theories of ontology engineering for capturing the essential conceptual structure of the target world. The SS ontology provides common terms, concepts, and semantics by which users can represent the contents with minimum ambiguity and interpersonal variation of expression. This is a typical application of ontology to give semantics for knowledge sharing in industry and research. A feature of such an approach is the use of ontology as infrastructure for knowledge representation.

It is important that the ontology captures the essential conceptual structure of the target world as generally as possible at Layer 1. Domain-specific terms

[1] The details have been described in Kumazawa et al.(2009)

[2] http://www.hozo.jp/

can be shared across domains by generalizing them and defining them in terms of general domain-independent concepts. Another important factor is the minimization of hidden and implicit knowledge. Causal chains, familiar to domain experts and often left implicit, can also be shared among experts in other domains in a machine-readable form by carefully decomposing them into individual links.

In this way, structuring knowledge in a domain-independent manner can improve readability, reusability, and interoperability of knowledge in the target world.

3.2. Structure of SS Ontology

Due to the emphasis on the problem-solving approach of SS (Clark 2007), Problem and Countermeasure against a problem are two of the SS ontology's top-level concepts. Also, when trying to solve a problem, a goal or goals for countermeasures must be set, and the existing conditions and impacts of the countermeasures must be evaluated explicitly or implicitly. Post evaluation as well as prior evaluation may result in finding new problems. Thus, we include Goal and Evaluation in the top-level concepts of the ontology.

In addition, we set Domain Concept as another top-level concept. In the SS ontology, the knowledge in the domain is not organized by individual fields or disciplines such as energy, climate, population, policy, or laws. Instead, it is organized by more general concepts, such as objects, activities, situations, and attributes, on the basis of ontology engineering theory (Mizoguchi 2004).

In the theory of ontology engineering, an ontology is composed of domain-specific concepts under the upper level concepts, which are highly domain-neutral. In this way, the ontology is organized in a domain neutral manner. Our ontology consists of five top-level concepts: Goal, Problem, Countermeasure, Evaluation and Domain Concept. Although they are SS-specific, they are sufficiently generalized to be independent of the targeted domains. Furthermore, while concrete occurrences and activities can be the sub concepts of Domain Concept, these concepts do not depend on the context of problem solving. By describing the world using two types of super concepts, independent of and dependent on the context of problem solving, we can represent any kind of countermeasures for sustainability that we would like to show. Domain-specific knowledge seen from a specific viewpoint can be represented by combining these concepts. Also, such a conceptual system can support generation of ideas for new concrete countermeasures that were not conceived of when the system was initially designed.

In the current implementation, SS ontology has 562 concepts and 14 hierarchy levels.

3.3. Divergent Exploration of SS Knowledge

(1) Conceptual Map Generation from Ontologies

At Layer 2, we structure SS knowledge from multiple perspectives through divergent exploration of the SS ontology. The SS ontology described in subsection 3.2 systematizes domain-neutral concepts and relationships at the primitive level, and knowledge viewed from a domain-specific viewpoint can be represented by combining those generalized concepts and relationships. Viewpoint-independent knowledge can also be generated from SS ontology due to the machine readable format of the ontology.

Based on this observation, we developed a conceptual map generation tool for exploring an ontology. The tool extracts concepts from the SS ontology and visualizes them as a user-friendly conceptual map that is drawn based on the viewpoints specified by the users. By bridging the gap between ontologies and domain experts, the tool realizes the functional specification for exploration at Layer 2.

Fig. 2 shows how the conceptual map generation tool extracts concepts from an ontology and visualizes them in a user-friendly format depending on the viewpoints in which the user is interested. We define a viewpoint as the combination of a focal point and an aspect. The focal point is a concept which the user chooses as a starting point of the exploration. The aspect is the manner in which the user explores the ontology. Because an ontology consists of concepts and the relationships among them, the aspect can be represented by a set of methods for extracting concepts according to their relationships with other concepts. We classify the relationships into *is-a*, *part-of* and *attribute-of* relationships, and we define two methods for each class of relationship for following the relationship upward or downward (See Table 1). The network represents the aspects that are in focus during the exploration. Fig. 2 shows the conceptual map generated in the above example. It expresses the result of an exploration from the viewpoint of "What kinds of problems are defined in the SS ontology? What are their targets? And, what countermeasures are being considered?"

In this way, the system can explore the ontology divergently and generate conceptual maps based on any specified viewpoint. Consequently, the system helps

Table 1 Aspects for Concept Extractions

Kinds of extraction	Related relationships	Commands in the tool
Extraction of sub concepts	*is-a* relationship	isa
Extraction of super concepts	*is-a* relationship	super
Extraction of concepts referring to other concepts via relationships	*part-of/attribute-of* relationship	"Name of relationships" which are of interest." (Multiple relationships are delimited with "|".) e.g., [target, target|place of occurrence]
Extraction of concepts to be referred to by some relationship	*part-of/attribute-of* relationship	":A category (name of a super concept) of concepts referred to by some relationship which are of interest." e.g.[:Problem],[:Countermeasure]

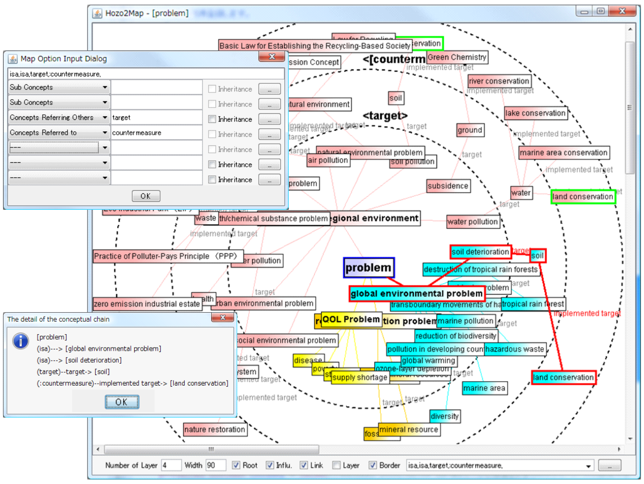

Fig. 2 A small example of conceptual map generation from the SS ontology.

users understand the extracted knowledge embedded in the ontology.

Our map generation tool has the following additional functions for helping users to explore ontologies[3]:

-Highlighting a specified conceptual chain.
By clicking a node, which represents a concept on the map, the tool highlights the conceptual chain from the focal point to the selected concept. The tool can also give the details of the conceptual chain in another window, as shown in Fig. 2. This function helps the user understand the relationships and the causal chains among concepts.

-Controlling the range of exploration.
The tool can manage the range of exploration by controlling the number of relationships that it traces for the exploration. In other words, viewpoint is managed based on the depth of the range of exploration.

-Linking a conceptual map with data stored at Layer 0.
The nodes in a conceptual map are based on the SS ontology at Layer 1. The tool can show related raw data at Layer 0 through the content management system we developed. Two kinds of linking are supported: annotated metadata and searches for keywords in documents.

(2) Trial Use of SS Ontology-based Mapping Tool

Using the developed mapping tool, we performed a trial of divergent exploration. The mapping outcome depends heavily on the quality of the ontology, so because the present ontology is still under development, it may be too early to conclude that divergent exploration using this tool is effective enough to generate meaningful multi-perspective conceptual chains. What we claim here is that this mapping tool has the potential to enable divergent exploration in the field of SS.

Fig. 3 shows a map with the minimum number of causal chains from *Problem* to *Countermeasure*. It was

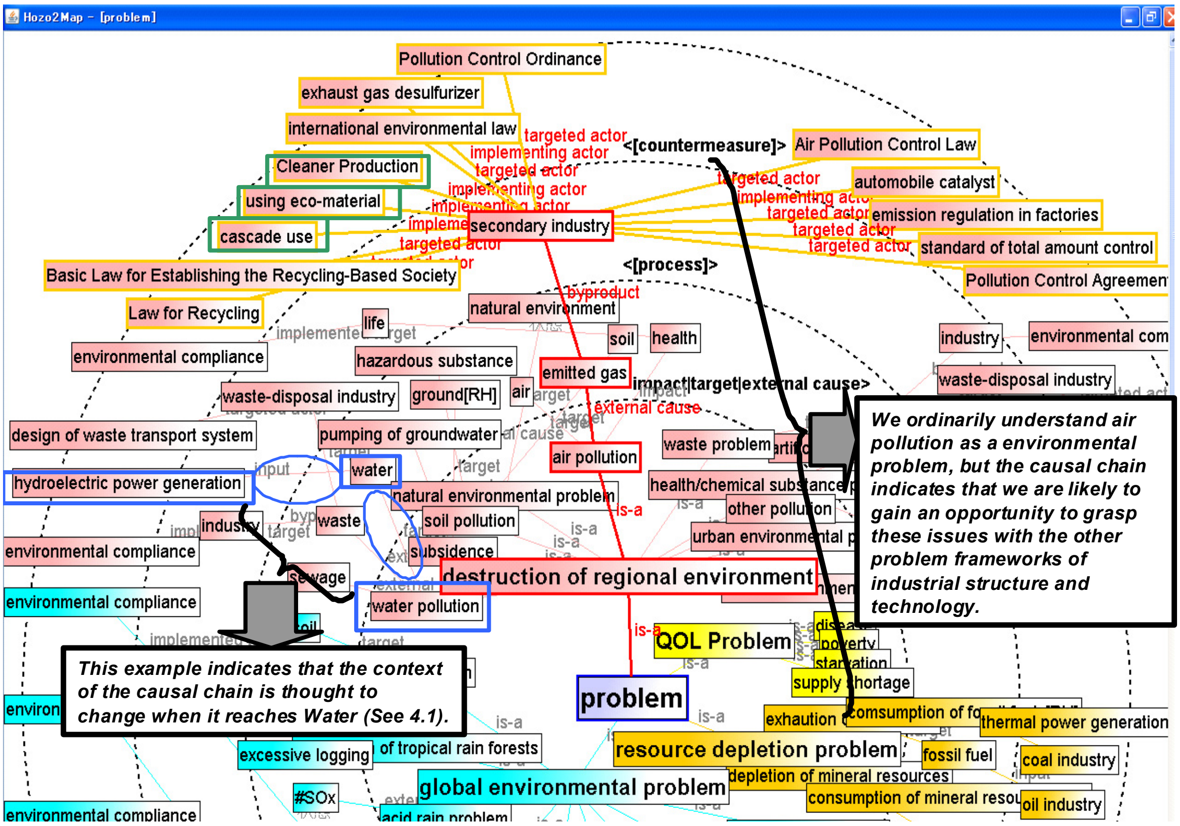

Fig. 3 Exploration of a conceptual map using *Problem* as a focal point.

[3] Even if the number of the concepts and the relationships of SS ontology increases, no problem occurs if the mapping tool is sufficiently developed. This is because the mapping tool set as a goal to present the structure of SS in accordance with the contexts users have.

generated by the command [<Problem> isa,isa,target|impact|externalcause, :process, :countermeasure], which means, "show me sub concepts of *Problem* to two levels and such chains that eventually reach sub concepts of *Countermeasure* through *target*, *impact*, or *external cause* relationships via sub concepts of *Process*." Consider the chains through *Air pollution. Air pollution* is connected to *Secondary industry* through *Emitted gas*, and there are thirteen countermeasures related to *Secondary industry*, including *Cleaner production*, *Using eco-material*, and *Cascade use*. In the map, these concepts are located around the important concepts in the context of industries among those related to sustainability This causal chain suggests that a context involving investigation of *Air pollution*, and *Regional environmental problem* as issues of sustainability in terms of industrial structure and technology may be of interest in SS.

4. Conformity Examination of an Ontology-based Sustainability Science Mapping Tool

4.1. Layers of the Reference Model

Layer 2 requires that we provide tools for exploring the conceptual world based on various perspectives in order to help the users, who are stakeholders related to issues on sustainability in divergent thinking. Here we discuss how the tool enables this exploratory inquiry in SS.

What kinds of inquiries characterize divergent thinking on SS? We selected eight types of questions that researchers in the field of SS might like to ask. Table 2 shows some example questions for two of the top-level concepts of the SS ontology: *Problem* and *Countermeasure*. Then, we checked whether the tool could generate an adequate map in accordance with those questions. The tool may fail to generate an appropriate map for a question either because the SS ontology has not been constructed sufficiently or because the function commands of the mapping tool do not work properly. The former is a Layer 1 issue and the latter is a Layer 2 issue. When we find the representation from a map to be inappropriate or insufficient, we discuss which reason is predominant.

Regarding inquiries (3) and (5), we found several points for improving the SS ontology and the mapping tool.

Inquiry (3) concerns a structural improvement of the ontology. For example, the map generated by the command "Problem (2 level depth) -target|impact|external_cause-> * -*-> process" shows both processes that cause a problem and processes that are influenced by the problem. Distinguishing between these processes requires interpretation, which means that not everyone will necessarily distinguish them in the same way. In addition, *Water* as a *target* is connected to both *Hydroelectric power generation* as a *process* and *Water pollution* on the map as a *Problem*. Hydroelectric power generation is only a process

Table 2 Sample Inquiries Concerning *Problem* and *Countermeasure*

(1) What kinds of issues/options are there regarding the problem/countermeasure?	
(2) What is the problem's subject? Or, what is the target object or subject of the countermeasure?	
(3)-1 (inquiries which a problem is a point of origin) How and why does the problem occur?	(3)-2 (inquiries which a countermeasure is a point of origin) How is the countermeasure implemented?
(4) What are the inputs of the countermeasure?	
(5) What kind of things, objects and/or subjects are related to the problem/countermeasure?	
(6) Who are the stakeholders of the problem?	
(7)-1 (inquiries which a problem is a point of origin) What kinds of countermeasures or alternatives are available for solving the problem?	(7)-2 (inquiries which a countermeasure is a point of origin) What other problems could the countermeasure contribute to solving?
(8) What problems must be solved before implementing the countermeasure?	

utilizing water, and it is neither target affected by water pollution nor a factor causing water pollution. At least from these causal chains, we cannot know whether deliberation about what hydroelectric power generation should be is required for the purpose of solving water pollution. The context of the causal chain is thought to change when it reaches *Water*. The improvement in what the causal chain on which such a switch occurs is not represented is thought to be needed.

Inquiry (5) concerns a functional improvement of the mapping tool. For example, the map generated by the command "Problem (2 level depth) -target|impact|external_cause-> * -*-> object"[4] shows that the problem of *Soil pollution* affects *Soil*, which is a basic element of *Ecosystem*, *Forest*, *Tropical rain forest*, *Rice field*, *Field*, and *Farmland*. In this way, the map can clearly show elements related to *Problem*. But *Tropical rain forest* is a sub concept of *Forest*, and *Rice field* and *Field* are sub concepts of *Farmland* on the ontology. The mapping tool needs to be improved so that we can grasp the super–sub relationship of the concepts. Furthermore, although the mapping tool treats *Ecosystem*, *Forest*, and *Farmland* in parallel, the ontology distinguishes *Ecosystem* as a sub concept of *Agent* from *Forest* and *Farmland* as sub concepts of *Natural construction*. Although *Ecosystem*, *Forest*, and *Farmland* share common elements such as plant and soil, they are ontologically different from one another in the sense that *Ecosystem* is an autonomous object while *Forest* and *Farmland* are targeted objects. The mapping tool needs to be modified to represent such distinctions.

4.2. Contribution to Reframing

We examine how the tool can contribute to reframing user's knowledge landscape. For example, a

[4] In this subsection we used the following expression format as a more intuitive notation. First, the move to the sub concepts at the deeper position of SS ontology is represented from by the sequence of "isa" is to by the depth of these concepts' hierarchy. For example, "isa, isa" is changed to the expression "(2-level deep)". Second, the reference to the slots is represented from by the "X" to by the "-X". For example, "input" is changed to the expression "-input". Third, the extraction of the concepts to be referred to by some relationship is represented from by ":Y" to by "* -*->Y". "*" means any class, "-*->"means any slot and this Y means a name of a super concept of concepts referred to by some relationship which are of interest. For example, ":problem" is changed to the expression "* -*->problem".

map using *Countermeasure* as a focal point can be generated by the command "Countermeasure (5-level deep) -implemented_target-> * -*-> object (2-level deep) -input-> * -*-> process -input|output -attribute-> * -*-> problem". According to this map, *Starvation* turns out to be one of the problems to be solved. The set of causal chains from *Countermeasure* to *Starvation* can be described by the following two linkages: [A] *Countermeasure –isa→Present countermeasure -isa→ Action-based countermeasure -isa→ Action other people cannot substitute -isa→ Management -isa→ Extracting environmental aspect –implemented_target→ Factory -*→ Automobile -isa→Four-wheel car -isa→ Ethanol vehicle –inpul→ Ethanol –*→ Biofuel production –input→ Corn -attribute→ Food -*→ Starvation* and [B] *Countermeasure –isa→Present countermeasure -isa→ Technology-based countermeasure -isa→ Individually handled-based countermeasure -isa → Pollutant removal technology -isa→ Exhaust gas desulfurizer –implemented_target→ SOx -* →Automobile -isa→ Four-wheel car -isa→ Ethanol vehicle input→ Ethanol –*→ Biofuel production –input→ Corn -attribute→ Food -*→ Starvation.* These sequences of conceptual chains might cause the user to rethink his or her mindset or assumptions regarding starvation. We can learn three points from these conceptual chains.

First, the set of causal chains can assist the users to re-scope an issue in the context of SS. *Biofuel production* and *Food* are connected by *Corn* in this example, which causes us to notice a trade-off relationship between *biofuel* and *food*. Although this kind of function is actually defined in Layer 3 of the reference model, the outcome of divergent exploration in Layer 2 may also contribute, depending on what issues we select.

Second, causal chains connect not only phenomena that occur at different locations but also different actors that are associated with each phenomenon. For example, chain [A] goes through *Extracting environmental aspects* and suggests that the implementation and the operation of an environmental management system may consequently be relevant to *Starvation*.

Third, the set of causal chains can help the users generate a new idea or hypothesis. For example, chain [B] describes a causal chain that includes the countermeasure of *Exhaust gas desulfurizer*. This unexpected result might stimulate the user's thinking.

In this way, we can increase our understanding of the target object or problem and maybe come up with a new idea or notice a hidden concept between the causal chains based on a more comprehensive overview of SS knowledge structure.

5. Concluding Remarks

5.1. Contribution to SS

As explained in subsection 3.2, our mapping tool enables divergent exploration, which in turn redefines problem setting and facilitates finding new problems for SS. This means that divergent exploration interconnects different domains and disciplines. It also functions as a dynamic inquiry process of the problems for SS because it indicates a new framework at each time of inquiry. Thus, the requirement that Layer 2 of the reference model for supporting problem identification be dynamic is satisfied.

The reference model supplies a co-evolutionary function that promotes interactive exploration of problems and knowledge, which reflects the essential property of SS. The reference model and the mapping tool based on it can, therefore, contribute to the development of SS by helping to clarify "what to solve" within the dynamic process of knowledge exploration.

Regarding the mapping tool, the interface that links different disciplines includes (a) links between concepts, (b) shared concepts of multiple disciplines, and (c) a common theoretical meta-model or framework that is referred to by researchers of different disciplines. These functions mediate different knowledge structures and also contribute to bridging multiple disciplines associated with SS. Therefore, these functions help to facilitate interdisciplinary collaboration, and to clarify "how to solve" within the dynamic process of knowledge exploration.

5.2. Challenges for the future

This paper addressed key challenges associated with knowledge structuring in SS, proposed a reference model, developed an ontology-based mapping tool as a solution to one layer of the reference model, and examined the tool's conformity to the reference model.

The focus of the mapping tool is to show the relationships between concepts broadly. But the present version of the tool may generate maps that are too visually complex, due to the large number of nodes. Now we are studying ways to add functions to the interface for simplifying the visual presentation of the maps, such as scoping nodes and chains according to user's concern.

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