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ORIGINAL ARTICLE

Toward knowledge structuring of sustainability science based on ontology engineering

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Abstract In sustainability science (SS), it is difficult to identify what needs to be solved, and it is also not clear how to solve the problems that are identified. There has been no consensus on the underlying question of "What is structuring knowledge in SS?" This paper focuses on knowledge structuring accompanied by supporting of thinking. It addresses the key challenges associated with knowledge structuring in SS, identifies the requirements for the structuring of knowledge, proposes a reference model, and develops an ontology-based mapping tool as a solution to one layer of the reference model. First, we identify the important requirements for SS knowledge structuring. Second, we develop a reference model composed of five layers based on three of the requirements. Third, we develop an ontology-based mapping tool at Layer 2 of the reference model for meeting the two major challenges for SS, namely, identifying what problems should be addressed in SS itself and proposing solutions for those problems. The tool is designed to store and retrieve information regarding SS, to provide access to a prototype ontology for SS, and to create multiple maps of conceptual chains depending on a user's interests and perspectives. Finally, we assess whether the developed tool successfully realizes the targeted part of the reference model for SS by examining the tool's conformity to the reference model, as well as its usability, effectiveness, and constraints. Although several issues were identified in the prototype ontology and the mapping tool, the study concluded that the mapping tool is useful enough to facilitate the function of Layer 2. In particular, the mapping tool can support thinking about SS from the viewpoint of: (a) finding new potentials and risks of technological countermeasures studied in SS; (b) helping users to get a more comprehensive picture of problems and their potential solutions; and (c) providing an effective opportunity to come up with new ideas that might not be thought of without such a tool.

Keywords Sustainability science · Knowledge structuring · Reference model · Conceptual map generation · Ontology engineering

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Introduction

A new scientific base is needed in order 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 "a comprehensive, holistic approach to identification of problems and perspectives involving the sustainability of global, social, and human systems." Their definition emphasizes the importance of a system's approach and addresses as SS's ultimate goal its contribution "to the preservation and improvement of the sustainability of these three systems" (Komiyama and Takeuchi 2006). In addition to this definition, we add two major characteristics to SS: orientation and scope.

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 the use of food crops as biofuels that require the simultaneous advance of knowledge and problems. Fourth, there are issues including the destruction of tropical rainforests that require the trade-offs between global and local problem-solving. Therefore, SS is a science tackling a number of challenges that existing disciplines have not experienced.

Regarding research orientation, SS is neither 'basic' nor 'applied.' It is an enterprise centered on 'use-inspired basic research' (Clark 2007). In this respect, SS can be characterized as problem-solving driven by the interplay of knowledge and actions in three systems. Furthermore, SS contributes to the quest for advancing useful knowledge and informed action simultaneously by creating a dynamic bridge between applied and basic research (Clark 2007).

The research scope of SS requires comprehensiveness. 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 the systematic reorganization of disparate existing fields. Thus, structuring knowledge is itself an important task for SS, which usually treats complex and evolving problems. Nonetheless, comprehensiveness cannot be achieved merely by structuring knowledge. Understanding requires consistent exploratory inquiry into a multitude of relevant domains, networking concepts in those domains in order to flexibly adapt to dynamic changes both within and between domains.

Given this definition and these characteristics 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. Nevertheless, we should not leave this weakness unexamined.

The Freiberg Workshop on Sustainability Science (Kates et al. 2001) identified seven core conceptual questions for SS. These questions include "How can the dynamic interactions between nature and society—including lags and inertia—be better incorporated into emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?" and "How are long-term trends in environment and development, including consumption and population, reshaping nature–society interactions in ways relevant to sustainability?" (Kates et al. 2001). The Global System for Sustainable Development (GSSD), developed at the MIT, is a system that shows 'what to solve' in the domain of sustainable development. It focuses "on the content-architecture—levels, linkages, and complexities—that characterized the domain of 'sustainability'" (Choucri 2003), and it is distributed as a global knowledge network on the Internet (http://gssd.mit.edu/). The Millennium Ecosystem Assessment (MA) was conducted between 2001 and 2005 to assess the consequences of ecosystem changes for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems (Millennium Ecosystem Assessment 2005). MA articulates nine key questions, including "How have ecosystems changed?", "How have ecosystem changes affected human well-being and poverty alleviation?", and "What options exist to manage ecosystems sustainably?" As another example of defining 'what to solve,' 100 ecological questions were identified as being of high policy relevance in the UK (Sutherland et al. 2006). Although this was a domestic effort, the policy creation process involved representatives from 28 organizations and scientists from 10 academic institutions who were asked to generate a list of 100 key questions through preparation activities, a 2-day workshop, and a screening process.

The second challenge of SS lies in identifying 'how to solve' the problems that are derived from the first challenge. Since the problems for SS, by their nature, relate to various stakeholders and players from many different fields, the problem-solving process requires the collaboration and partnership of these players. Therefore, interdisciplinary research is a common approach in this field where problems and questions are not confined to a single discipline. 'Interdisciplinary' is distinguished from 'multidisciplinary' in that, while interdisciplinary research promotes interaction and may forge a new research field or discipline, multidisciplinary researchers go their separate ways and remain unchanged when collaborative work on a common problem is completed (National Academy of Sciences 2005). Considering the research motivation and purpose of SS, interdisciplinary research is preferable to multidisciplinary research, but even multidisciplinary research often encounters difficulties and does not work as expected, especially in its initial phase. For example, a few years ago, the authors organized a research project to develop sustainable future scenarios as well as the assessment criteria for sustainability. Both environmental economists and environmental engineers participated. As the research project progressed, we found that the environmental economists' approach to the goals and countermeasures was fundamentally different from that of the environmental engineers' approach. The economists tended to feel uncomfortable accepting the scenario approach adopted by the engineers, who attempted to capture the richness and range of possibilities in an uncertain future society from which to conceive methods aimed at avoiding or reducing the potential risks of the scenarios. They were more interested in discussing how to achieve given policy targets, such as a 20% CO_2 reduction by the target year with minimum social cost or how to attribute cost to different social sectors and players in an economically sound way.

The background of these two major challenges, both 'what to solve' and 'how to solve,' is not yet clear enough to assemble various disciplines into SS. Moreover, we recognize that there has been no consensus on the underlying question of "What is structuring knowledge in SS?" in the first place. In other words, SS researchers are neither sure of 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. Sharing explicitly structured knowledge about SS among scientists from various disciplines is crucial to facilitating collaboration for interdisciplinary SS.

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 inadequate for meeting these SS needs because those systems are mainly static structures representing SS and have no link to tools for supporting problem finding and solving. In addition, existing systems target knowledge in specific domains or consist of contents divided into respective research fields. As a result, when we use those systems, we are compelled to collaborate within a specific domain.

In order to remedy this situation, we need to design a new conceptual framework to structure knowledge for facilitating collaboration in SS, to develop a knowledge system for SS as an implementation of the framework, and to verify and validate the system. If researchers from different fields use such a knowledge system in the process of interdisciplinary research in SS, and if the system can support their thinking by structuring knowledge, then this support would facilitate collaboration and the establishment of partnerships between them.

As an initial step to meeting these needs, 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. In "Reference model for knowledge structuring in sustainability science", we identify the requirements and establish a five-layer reference model as a development roadmap for structuring knowledge in SS. In "Structuring sustainability science with ontology engineering technology", we develop an ontology-based knowledge system and mapping tool to illuminate multi-perspective conceptual chains. In "Conformity examination of an ontology-based sustainability science mapping tool", we examine the tool's conformity to the proposed reference model and discuss its usability, effectiveness, and constraints. During the process of developing the knowledge system, we have created a prototype SS ontology. Due to the space limitation, we defer explanation and discussion of the detailed development procedures and scientific significance of the SS ontology itself to another paper. The main focus of the research presented in this paper is to create a rationale for SS knowledge structuring and apply ontology engineering to develop a knowledge system that facilitates addressing 'what to solve' and 'how to solve' for SS.

Reference model for knowledge structuring in sustainability science

Requirements for knowledge structuring in sustainability science

First, we must answer the question "How can we identify necessary conditions and functions for knowledge structuring in SS as development requirements?" (Berztiss 1992). The requirements can be described from two perspectives; one related to the knowledge architecture itself and the other concerning the functions required to support users.

The first perspective can be examined from three sub-perspectives: 'whenever,' 'whatever,' and 'whoever.' By 'whenever,' we mean that structured knowledge should be reusable. Thus, *reusability* is one of the requirements for SS knowledge structuring. 'Whatever' implies that structured knowledge should be applicable to as many different domains as possible, not just to a specific domain or discipline, due to the multidisciplinary and interdisciplinary characteristics inherent to SS (Komiyama and Takeuchi 2006). This feature should be interpreted as *versatility*, which is also required for SS knowledge structuring. As Hasumi (2001) points out, the concept of sustainability should be understood by its diversity due to the complexity of the problem it treats. This means that, while seeking *versatility*, one often enacts simplification; however, it is also necessary to maintain sufficient diversity and complexity to characterize the original problem. *Versatility* for SS knowledge structuring is, therefore, needed to express a situation without losing its diverse contents, while using a set of rules that are as simple as possible. By ‘whoever,’ we mean that anyone should obtain the same result, as long as he or she traces the same structuring process and procedures. Such *reproducibility* is required to verify the structuring process, as is the case with any scientific procedure.

Since SS treats evolving problems that require dynamic redefinition of the problem’s domain by consistent networking of knowledge and actions, the SS knowledge structure must be extensible in order to meet unpredictable future changes of the domain. As knowledge changes over time, its representations must adjust accordingly (Choucri et al. 2007). Thus, *extensibility*, which includes adjustability, is the fourth imperative of SS knowledge structuring.

The second perspective relates users, who are the main actors, with their actions for SS. The larger the number of people who share the structured knowledge, the larger the common base of SS becomes. *Availability* should, thus, be the fifth requirement. If the SS knowledge structure is available on the Web as an open meta-content, as is *Mapping Sustainability* (Choucri 2003), *availability* would be high. Besides, actions concerning SS knowledge structuring can be subdivided into actions to access the SS knowledge structure and actions to interpret it. Access is ensured by the fulfillment of *availability*, so *interpretability* becomes the sixth requirement. By *interpretability*, we mean that the SS structured knowledge should help its users understand a problem and find an appropriate approach to its solution.

Ontology-based knowledge structuring

Information technology (IT) can provide effective methods for knowledge structuring. Some of the requirements discussed in “Requirements for knowledge structuring in sustainability science”, such as *reusability*, *reproducibility*, and *extensibility*, are easily satisfied using computer systems. For knowledge structuring using IT, raw data stored in computers to reflect the real world are structured for efficient utilization. In the case of SS, which covers a large number of domains, well-organized knowledge is necessary for the efficient systematization of concepts that are hidden in the data. As the knowledge is shared and circulated across various domains, large intellectual assets are formed that lay the foundation for the idea that “Knowledge is Power” (Hendler 2006). One of the key technologies for organizing a conceptual world is ontology engineering, which is expected to contribute to the structuring of the knowledge in the target world. This paper proposes an initial transition of SS in this direction.

As we mentioned in the “Introduction”, in SS, it is often difficult to identify the problem to solve. We cannot take a quantitative approach because concepts and their relationships are not clear. One effective approach is to use a tool for supporting the thinking process for identifying what to solve. For example, the use of an ontology can help modelers select appropriate variables during the construction of a simulation, and ontology engineering can also help to combine models constructed separately. Furthermore, an ontology functions as the platform for smoothing communication among stakeholders. Thus, ontology engineering is characterized as a tool for supporting thinking.

Ontology is defined as an “explicit specification of conceptualization” by Gruber (1993). The construction of a well-designed ontology presents an explicit understanding of the target world that can be shared among people. That is, the essential conceptual structure of the target world is understood through its ontology. Ontology engineering provides a theory of ontology that can answer questions such as “What should an ontology be?” and “How can we capture the real world appropriately?” Based on ontology engineering, a wide range of knowledge can be organized in terms of general, highly versatile concepts and relationships. Ontologies also provide flexible expressiveness that can convey social phenomena, which are difficult to formulate with quantitative methods. On the basis of these observations, we adopted an ontology-based approach to systemize knowledge for the knowledge structuring of SS.

Development of a reference model for knowledge structuring in sustainability science

Based on the identified requirements (“Requirements for knowledge structuring in sustainability science”) and ontology engineering technology (“Ontology-based knowledge structuring”), we propose a reference model for SS knowledge structuring to support idea generation for problem finding and solving.

Sustainability science should be defined not by the domains it covers but by the problems it tackles (Clark 2007). Due to the complexity and diversity of sustainability issues, it is important to identify and evaluate relationships between problems, causes, impacts, solutions, and their interactions. Those relationships usually depend on the specific context of an individual case or problem. Problems and their solutions need to be explored within each problem's specific context.

Therefore, SS knowledge needs several kinds of structural and methodological information for problem finding and solving, as well as information about the raw data. Structural information can be divided into the underlying static information structure of SS and the dynamic information linked with human thought. The dynamic information can then be divided into information that reflects individual perspectives and information that organizes these perspective-based information structures within a specific context. Methodological information refers to information that facilitates problem finding and solving based on these contextualized information structures.

We propose a reference model that consists of layers corresponding to these 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 Schlieder have verified the conformity between reference models and their domain models on a specific domain (Hess and Schlieder 2006). In this paper, we focus on developing a reference model of the knowledge structuring approach for SS.

As shown in Fig. 1, the reference model 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 vocabulary 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.

Some kind of guidance is needed to support problem finding and getting ideas. Guilford (1950, 1967) classified human thinking into divergent thinking and convergent thinking. We assimilated these concepts into our reference model: divergent thinking is supported at Layer 2 and convergent thinking is supported at Layer 3.

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

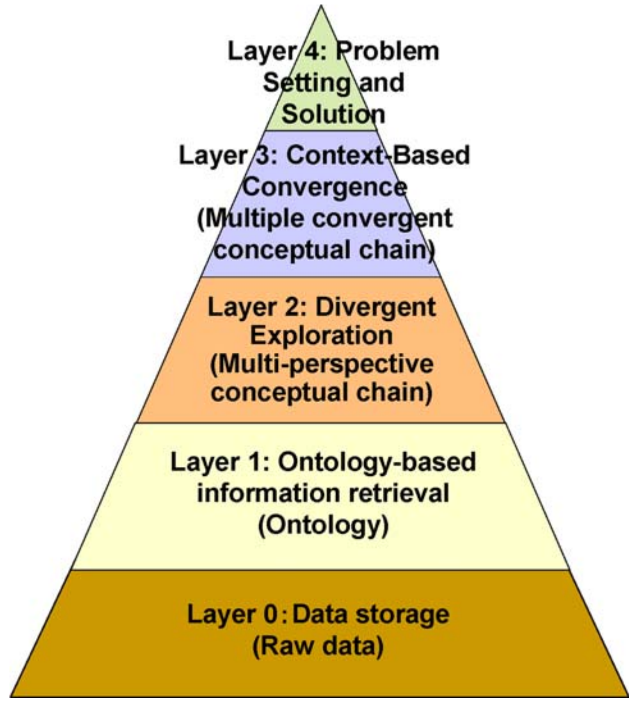

Fig. 1 Layered structure of the reference model

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. The ontology at Layer 1 must contribute to such exploration. Divergent exploration can be performed by obtaining what we call 'multi-perspective conceptual chains' through the selection of arbitrary concepts according to the explorer's intention. Many ways of tracing the conceptual chains may be needed for handling the various aspects of SS.

After collecting such 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 to the given context. Examples of contexts include the social and environmental settings of a specific problem, implemented or planned countermeasures and policies for solving a problem, and even trade-offs between different goals, such as food security and biofuel production.

At Layer 4, using all of the information and knowledge obtained at the sub layers, 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 the abduction of new hypotheses.

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. We believe that a static structure is inadequate for handling the multi-perspective nature of SS. Another characteristic of the reference model is its layered structure, in which each layer is composed of a pair made up of structured information and a task. This reflects our understanding of SS as being inherently problem- and use-inspired basic research.

Structuring sustainability science with ontology engineering technology

Knowledge structuring framework based on the reference model

We applied the reference model to develop a knowledge structuring system for SS. For Layer 0, we collected a comprehensive sample of literature and databases available on the Web. This work was conducted in parallel with the activities of the Research Institute for Sustainability Science (RISS) at Osaka University (Morioka et al. 2006) to develop a meta-database of SS, a conceptual map on the resource-circulating society, and educational contents of a core module for SS, under the name "Valuation Methods and Technical Aspects in Sustainability."

As a prototype tool at Layer 1, we constructed a trial SS ontology. For this, we first extracted the concepts for SS ontology and the relationships between these concepts from the meta-database of SS, the documents used as educational contents, and the database on the Environmental Information and Communication Network website (http://www.eic.or.jp/). Second, we discussed the architecture of the SS ontology and requirements for SS knowledge structuring in monthly workshops coordinated by the RISS since the year 2006. The detailed process for constructing the SS ontology will be reported in a future paper. Based on the information collected and the discussion in the workshops, a prototype version of SS ontology was built as a required task at Layer 1. We conducted several kinds of research studies that are necessary for applying an ontology to a sustainability domain, including targeting sustainable development indicators, risk communication, and education (Brilhante et al. 2006; Friend 1996; Macris and Georgakellos 2006; Suzuki et al. 2005; Tiako 2004).

Semantic web technology has been applied to develop systems for knowledge structuring and data retrieval. For example, EKOSS, which stands for expert knowledge ontology-based semantic search, is a knowledge-sharing platform based on semantic web technologies (Kraines et al. 2006). In order to realize the specification of Layer 2, we also developed a conceptual mapping tool that enables a user to explore the SS ontology from that user's particular perspective and to generate a conceptual map accordingly. The following sections titled "Ontology-based information retrieval" and "Development of the sustainability science ontology" explain this developmental process and its outcomes.

Ontology-based information retrieval

Figure 2 shows an overview of our knowledge-structuring tool based on ontology engineering. For Layer 1, we developed an ontology-based information retrieval system. It manages real data at Layer 0 using common concepts that are systematized in the SS ontology and realizes knowledge sharing and exchange across domains.

We constructed SS ontology using an ontology development tool named Hozo (http://www.hozo.jp/), which is based on fundamental theories of ontology engineering for capturing the essential conceptual structure of the target world. Hozo has more than 1,500 users around the world, and it has been used to implement various ontologies for functional design, oil refinery plant, genomics, medicine, learning and instructional theories, and so on. The features of Hozo include: (1) supporting role representation (Mizoguchi et al. 2007), (2) visualization of ontologies in a friendly GUI, and (3) distributed development based on the management of dependencies between ontologies (Kozaki et al. 2007a). Hozo's native language is an XML-based frame language, and ontologies can be exported in OWL and RDF(S). As an example, Matsui et al. (2007) created an ontology on interdisciplinary risk research and environmental systems using the Hozo platform.

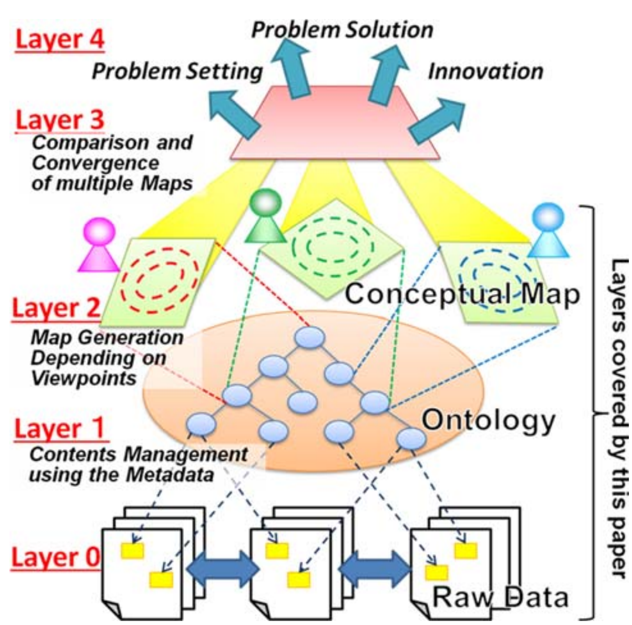

Fig. 2 An overview of the knowledge-structuring tool based on ontology engineering

We also developed a content management system for knowledge sharing and systematic information retrieval based on the SS ontology (Kozaki et al. 2007b). We used the system to manually annotate the raw data at Layer 0, with metadata defined in terms of the concepts in the SS ontology using semantic web technology. Users can systematically manage and search the content through the metadata. They can also find related contents by referring to the relationships between the concepts defined in the ontology. Furthermore, they can get an overview of the contents stored at Layer 0 by counting the numbers of contents related to each concept. Currently, we are using only simple annotation data, such as keywords, but in the future, we will improve the system so that we can manage more kinds of content and use it in a larger scale application.

At Layer 1, 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. For example, Dzbor et al. (2003) developed a semantic web browser named Magpie, which uses ontologies as common thesauri for navigating users to related web pages based on their semantics. The System for Environmental and Agricultural Modelling; Linking European Science and Society (SEAMLESS) integrates project constructs into the model interface ontology and links various environmental models based on those constructs (Athanasiadis et al. 2006). A common feature of these approaches is the use of ontology as an infrastructure for knowledge representation.

At Layer 1, it is important that the ontology captures the essential conceptual structure of the target world as generally as possible. Domain-specific terms 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. For example, causal chains, familiar to domain experts and often left implicit, can be shared with 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 the readability, reusability, and interoperability of knowledge in the target world.

Development of the sustainability science ontology

1. Constituents of ontology

The main contribution of this paper is to propose a reference model for structuring SS knowledge and to introduce a mapping tool based on that model. For this, an analysis of the quality of ontology is not essential, and, so, we only briefly explain the conceptualization of terms needed for structuring the SS ontology. An ontology consists of concepts and relationships that are needed to describe the target world. One of the main components of an ontology is a hierarchy of concepts representing things existing in the target world that are determined to be important and organized by identifying *is-a* relationships between them.

Figure 3 shows a small section of the SS ontology. In the example, an *is-a* relationship declares that *Destruction of regional environment* is a kind of *Problem*. In the *is-a* relationship, the generalized concept (e.g., *Problem*) is called a *super concept* and the specialized concept (e.g., *Destruction of regional environment*) is called a *sub concept*. Thus, an *is-a* hierarchy describes the categorization of the concepts. For instance, *Problem* is subdivided into sub concepts such as *Destruction of regional environment* and *Global environmental problem*. Furthermore, *Destruction of regional environment* is subdivided into *Air pollution*, *Water pollution*, and so on.

The introduction of other relationships refines the definition of the concepts. For example, *part-of* relationships, which are also called *has-part relationships*, and *attribute-of* relationships are used to show the concept's parts and attributes, respectively. These relationships can be used to explicate the *is-a* relationships that give the categorization. For example, in contrast to Case 1, Case 2 in Fig. 3 explicates that the categorization of *Problem* is determined by the *place of occurrence*, which is represented using an *attribute-of* relationship for *Destruction of regional environment* and *Global environmental problem*. One difference between *Air pollution* and *Water pollution* is the

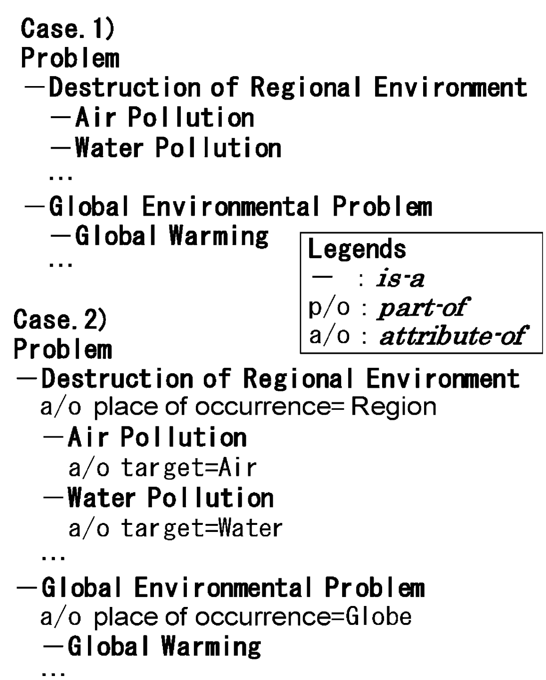

Fig. 3 A small example from the sustainability science (*SS*) ontology

target, which is also represented using an *attribute-of* relationship. In this example, *place of occurrence* and *target* are examples of a relationship, called a *role*. These relationships and roles are described as slots in Hozo.

When there is an *is-a* relationship between two concepts, the sub concept inherits the *part-of* and *attribute-of* slots from its super concept. In Fig. 3, definitions of *Destruction of regional environment* (e.g., "a/o place of occurrence = region") are inherited by its sub concepts, such as *Air pollution* and *Water pollution*. The inherited slots can be specialized by a sub concept. For example, *Destruction of Satoyama*, a traditional rural landscape in Japan, inherits "a/o place of occurrence = region" from its super concept *Destruction of regional environment* and specializes it to "a/o place of occurrence = Satoyama."

In this way, concepts can be defined during the process of ontology building through inheritance and specialization.

2. Basic structure

Due to the emphasis on the problem-solving approach of SS, *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 a new problem. 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 2003, 2004a, b).

In ontology engineering theory, 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, domain-independent and domain-dependent, we can represent any kinds 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 the generation of ideas for new concrete countermeasures that were not conceived when the system was initially designed.

3. Prototype of SS ontology

Using Hozo as an application platform, we have developed a prototype of SS ontology. It is not our intention in this paper to present a fully developed SS ontology. However, we briefly explain the top-level concepts and second-level concepts with the slots, which are concepts of parts and attributes, that are used to describe them. In the current implementation, SS ontology has 562 concepts and 14 hierarchy levels.

(i) *Problem*

(a) Top- and second-level concepts.

Problem is categorized into *Resource depletion problem*, *Global environmental problem*, *Regional environmental problem*, and *Quality of life-related problem*. We admit that this composition of sub concepts is strongly influenced by environmental science, which is an established discipline, so it currently confines sustainability problems mainly to environmental ones. This classification will need to be augmented to cope with more complicated and diverse sustainability issues.

(b) Slots for explicating *is-a* relationships (parts and attributes).

In order to explicate the *is-a* relationship of *Problem* with its sub concepts, we added slots for *target* and *site*. We also added *internal cause*, *external cause*, and *impact* as attribute slots. We confined ourselves to counting only the direct impacts of a given problem.

(ii) *Goal*

There are two approaches to defining the top-level concept of *Goal*: one is to describe a situation that people desire, and the other is to describe an ideal social structure or system. The former approach often uses phrases such as *Global peace* and *Human happiness and well-being*. The latter approach includes goals that, for example, articulate the social structure for a *Resource-circulating society* (Ministry of the Environment, Japan 2007) or specify the range of *Environmental carrying capacity*. We named these two approaches *Situational goal* and *Structural goal*, respectively.

(iii) *Evaluation*

Sub concepts of *Evaluation* consist of *Evaluation perspective*, *Value*, *Evaluation indicator*, and *Evaluation method* (Rotmans 2006; UNEP CBD 2000). *Evaluation indicator* was also subdivided into five types: *Qualitative indicator*, *Quantitative indicator*, *Warning indicator*, *State indicator*, and *Indicators and time* (Munier 2005).

(iv) *Countermeasure*

(a) Top- and second-level concepts.

Countermeasure is divided into two major sub concepts: *Future-oriented countermeasure* and *Present/Ongoing* *countermeasure*. The former includes *Scenario*, *Education*, and *Plan*. *Education* is considered as a measure for training future generations who will be responsible for implementing necessary actions in the future. The latter focuses on the relationship between people and technology. Countermeasures in this sense consist of technologies, people, and interconnections between all kinds of actions associated with technologies. Countermeasures concerning people, for example, include restrictions of their actions and changes of their behavior. The sub concepts of *Present/Ongoing countermeasure* are *System-based countermeasure*, *Technology-based countermeasure*, *Action-based countermeasure*, and *Conversion of styles*.

(b) Slots for explicating *is-a* relationships (parts and attributes).

implemented target, *implementing actor*, *implemented place*, and *targeted actor* are slots of *Countermeasure*.

(v) *Domain Concept*

(a) Top- and second-level concepts.

Domain Concept is divided into several abstract concepts, such as *Quantity*, *Attribute*, *Abstract object*, *Concrete thing*, *Substrate*, and *Spatial region*. These are typical concepts used in top-level ontologies. *Concrete thing* is divided into *Object* and *Process*.

We have chosen *Agent*, *Artificial object and Material* and *Natural construction* as the sub concepts of *Object*. *Agent* has two concepts called *Macro agent* and *Micro agent*. Concepts of systems, such as *Social system*, *Ecosystem*, and *Industrial Ecology*, are sub concepts of *Macro agent*. *Artificial object and Material* is subdivided into *Artificial object*, which includes *Building*, *Urban infrastructure*, and *Transportation infrastructure*, and *Substance-resource*, which includes *Substance* and *Resource*, etc.

The sub concepts of *Process* include *Activity*, *Phenomenon*, *Circulation*, and *Situation*. *Activity* is divided into four concepts: *Life*, *Production process*, *Industry*, and *Action*. *Circulation* is divided into three concepts: *Material circulation in the natural environment*, *Material circulation based on economic activity*, and *Circulation of life*.

(b) Slots for explicating *is-a* relationships (parts and attributes).

Process is specified using slots for *input* and *output*.

Divergent exploration of sustainability science knowledge

1. Divergent exploration of knowledge depending on multiple viewpoints

At Layer 1, the SS ontology has been designed to provide an explicit conceptual structure and machine-readable vocabulary of domains for knowledge structuring. While it was built using domain-neutral concepts to capture the essentials of SS in general, experts often want to understand the target world from domain-specific viewpoints.[1] Even experts in the same domain will often have different interests. Therefore, it is desirable to structure knowledge not only from the general perspective, but also from multiple domain-specific perspectives so that experts from multiple domains of SS can easily understand the structured concepts.

At Layer 2, we structure SS knowledge from multiple perspectives through divergent exploration of the SS ontology. The SS ontology described in "Development of the sustainability science ontology" 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.

2. Conceptual map generation from ontologies

Figure 4 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).[2]

[1] By domain, we mean a discipline such as energy, climate, population, policy, or laws.

[2] For example, if we gives the command [<Sea level rise> super,super,isa], the map shows the following chain: *Sea level rise* –super → *marine problem* –super → *natural environmental problem* –isa → *forest issue*, *disruption of ecosystem*, or *marine problem*. In this way, combining the commands 'super' and 'isa,' we can trace the chain from one concept and another one at the same hierarchy level.

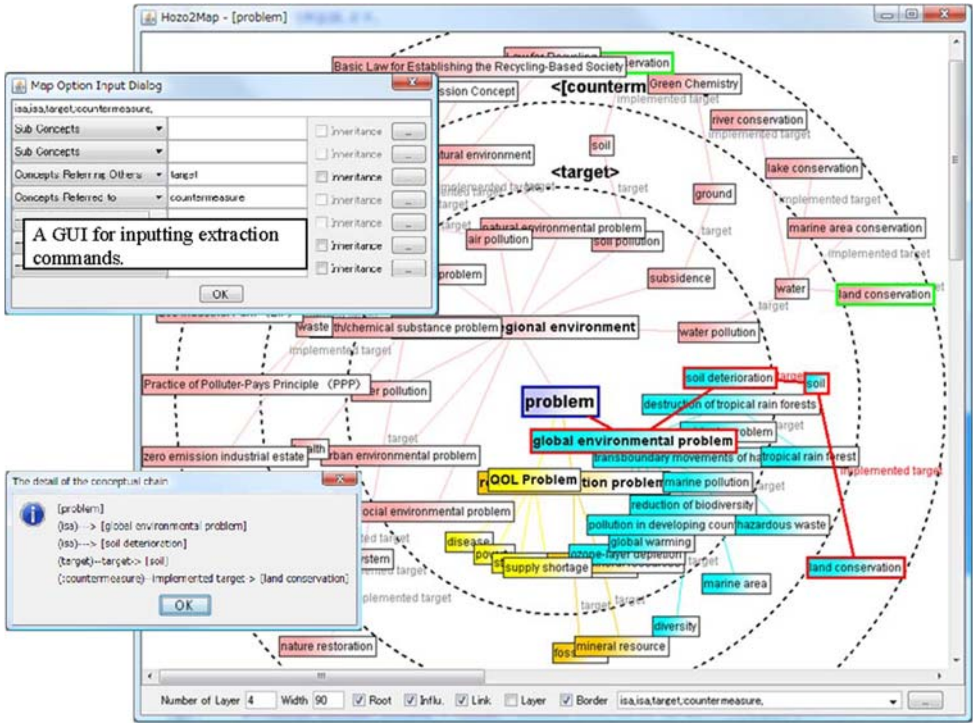

Fig. 4 A small example of conceptual map generation from the SS ontology

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 "|".)	"A category (name of a super concept) of concepts referred to by some relationship which is of interest." (Under development)
Extraction of concepts to be referred to by some relationship	*part-of*/*attribute-of* relationship	"Name of relationships which are of interest." (Under development.)	"A category (name of a super concept) of concepts referred to by some relationship which is of interest."

Consider the following example. If we set *Problem* in Fig. 3 as the focal point and extract its sub concepts, then concepts such as *Destruction of regional environment*, *Global environmental problem*, and so on are extracted. Next, by tracing the concepts referred to by the *attribute-of* relationship *target*, concepts such as *Water* and *Soil* are extracted. Finally, if we explore all of the chains from any concept extracted thus far to sub concepts of *Countermeasure*, then concepts such as *Automobile catalyst* and *Green Chemistry* are extracted. The command for this concept extraction process is made by combining the above sub commands, which gives the command [<Problem> isa, isa, target, :*Countermeasure*]. Here, the number of 'isa' sub commands determines how many steps the system will follow the *is-a* relations in the ontology. In this example, the command states that the map should follow only two *is-a* relations, even if the *is-a* tree of *Problem* has a depth of more than two. If the user wants to see a more detailed map about *Problem*, he/she may add more 'isa' sub commands. In order to make the following analyses easier to understand, we will use the following expression format as a more intuitive notation. First, the command to extract sub concepts at the deeper position of the SS ontology is changed from a sequence of 'isa' expressions to a number giving the depth of the concept hierarchy. For example, 'isa, isa' is changed to the expression '(2 level depth)'. Second, references to slots are changed from 'X' to '-X-> Y', where X is the slot and Y is the concept that fills the slot. '*' means any concept class and '-*->' means any slot. For example, 'input' is changed to the expression

'-input->*'. Third, the extraction of the concepts to be referred to by some relationship is changed from ':Y' to '<-X-Y', where X is the name of the relationship and Y is the name of a super concept of concepts of interest that are referred to the relationship X. For example, ':*Problem*' is changed to the expression '<-*- *Problem*'. Using this format, the command is '*Problem* (2 level depth) -*target*-> * <-*-*Countermeasure*'. The user can also input the commands by choosing aspects using the GUI shown in the upper left of Fig. 4. A new version currently under development will provide users with more detailed options for concept extraction. For instance, users will be able to trace the chains within a range of specific concepts. In order to improve the usability of the system, future versions will let users select aspects using a point-and-click GUI.

From the extraction of concepts based on a viewpoint, the system obtains conceptual chains that match with the user's interest. The conceptual chains are visualized as a conceptual map. In the conceptual map, the focal point is located in its center, and the conceptual chains are represented as a divergent network. The nodes and links of the network show how the extracted concepts and relations between them represent different aspects of the conceptual chains, i.e., the relationships followed and the concepts selected (Fig. 4).

The network represents the aspects that are in focus during the exploration. Figure 4 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 viewpoint. Consequently, the system helps users understand the extracted knowledge embedded in the ontology.

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

- 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. 4. 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 controling the number of relationships that it traces for the exploration. In other words, the 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 discussed in "Ontology-based information retrieval". Two kinds of linking are supported: annotated metadata and searches for keywords in documents.

Through these functions, multiple conceptual maps can be generated from the SS ontology based on various viewpoints that help users to understand the SS knowledge systematically across domains. Because these maps are generated exhaustively by the computer, they could contribute to a discovery of unexpected causal chains that were not known to the explorers.

Trial use of the sustainability science 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.

Figure 5 shows a map with the minimum number of causal chains from *Problem* to *Countermeasure*. It was generated by the command '*Problem* (2 level depth) -target|impact|external cause-> * <-*- *Process* <-*- *Countermeasure*', which means, "show me sub concepts of *Problem* to two levels (the innermost circle) and such chains that eventually reach sub concepts of *Countermeasure* (the outermost circle) through *target*, *impact*, or *external cause* relationships to any concepts (the second circle) via sub concepts of *Process* (the third circle)." Consider the chains through *Air pollutant*. *Air pollutant* is connected to *Secondary industry* through *Emitted gas*, and there are 13 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 the investigation of *Air pollutant*, *Air pollution*, and *Regional environmental problem* as issues of sustainability in terms of industrial structure and technology may be of interest in SS.

Sharing particular concepts in the context of sustainability this way is expected to facilitate the establishment of interdisciplinary collaborations. For example, a map using *Countermeasure* as a focal point was generated by the command '*Countermeasure* (5 level depth) -implemented target-> * <-*- *Object*<-*- *Problem*', which means, "show me sub concepts of *Countermeasure* to four levels and such

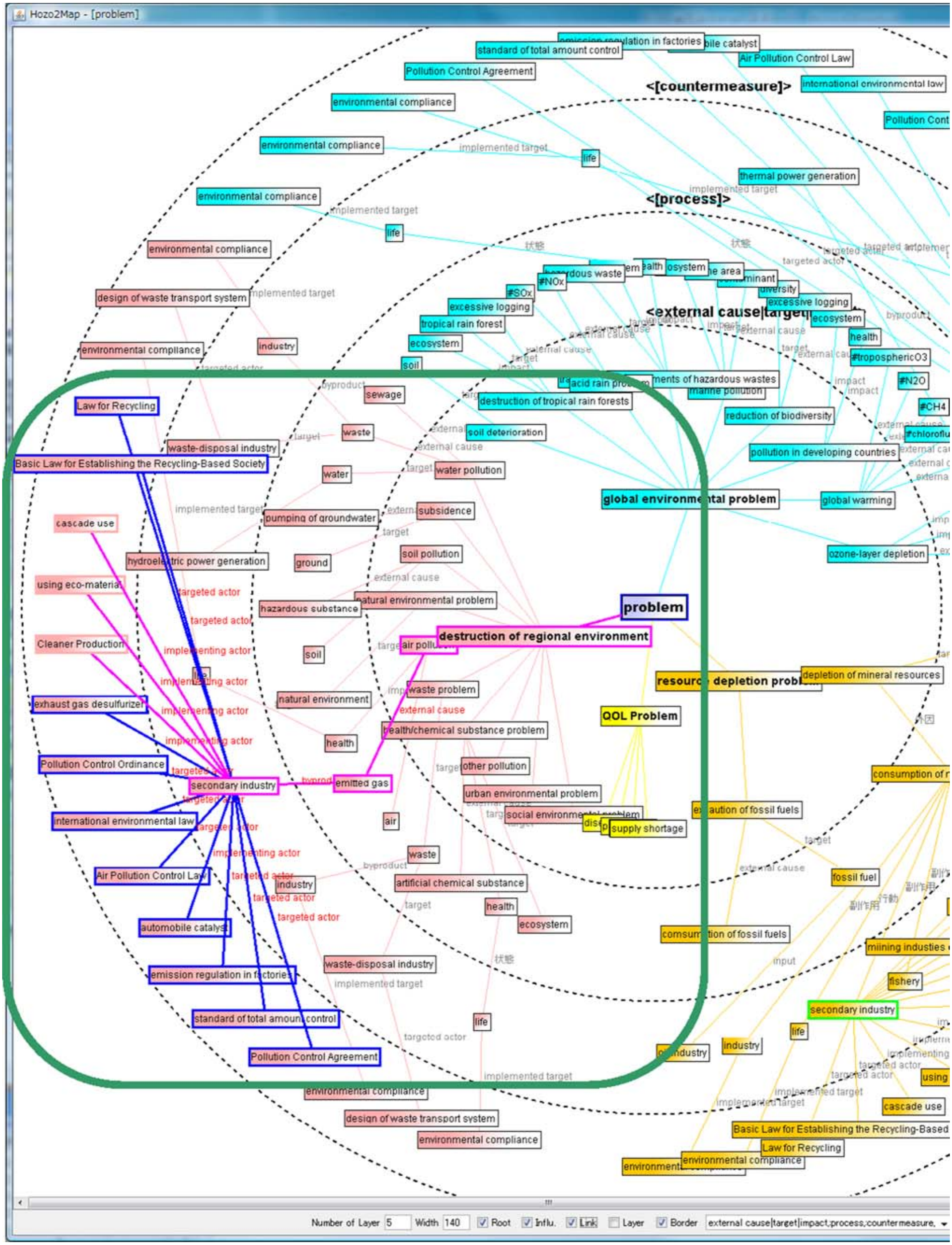

Fig. 5 Exploration of a conceptual map using *Problem* as a focal point

chains that eventually reach sub concepts of *Problem* through *implemented target* relationships to any concepts via sub concepts of *Object*.' Among the many chains, the chain passing through *Ecosystem* includes not only concepts related to *Creature* but also concepts in other disciplines. This chain not only shows the importance of the assessment of the ecological state but also suggests that such an assessment must be performed from multiple perspectives, thereby, requiring the participation of experts from different disciplines (Millennium Ecosystem Assessment 2005).

It is hard for domain experts to understand what is in even a small-scale ontology. The mapping tool makes the ontology more easily available to them because it can show the causal linkages between concepts in the ontology from different angles according to the point of focus. The mapping tool was developed not for understanding strict definitions of concepts, but for exploring 'the ocean of concepts' described by the ontology. There are various tools for constructing ontologies, such as Protégé.[3] These tools are useful for confirming the strict definitions of individual concepts, but they are not suitable for exploring a map of concepts and for showing an overview of the linkages.

However, there are many points to improve, such as how to show the map and how to support user interaction. Once we have realized an exhaustive SS ontology, we can imagine that an enormous number of causal chains will be found. We will explore methods for using the mapping tool to visualize maps with such large numbers of causal chains more clearly or simply to verify what types of maps are most useful to users through user experiments.

In the future, we will link the chains shown on the mapping tool to the content management system, which contains only linkages between the data contents and the concepts of SS ontology now. We will use this linkage for scoping the contents. To do this, we will first add the relationships among keywords to the metadata, thereby, making the metadata correspond to the conceptual chains at a higher degree. Next, we plan to show on the mapping tool the contents having a high degree of coincidence between a chain on the conceptual map and the metadata of the selected concepts. We are also developing a function for comparing multiple maps, but it is still at a prototype level.

Conformity examination of an ontology-based sustainability science mapping tool

Compliance with knowledge-structuring requirements

In "Requirements for knowledge structuring in sustainability science", we identified six requirements for SS knowledge structuring: *reusability*, *versatility*, *reproducibility*, *extensibility*, *availability*, and *interpretability*. *Reproducibility* and *extensibility* are satisfied due to the fact that the ontology and maps have been developed as part of a computer-based ontology generation and knowledge management system, named Hozo. *Reusability* is guaranteed to some degree by the relative stability and domain-independence of the SS ontology.

When developing the SS ontology, we tried to choose generalized concepts that are not dependent on a specific scientific domain or field. In this sense, *versatility* has been achieved partially, but several parts, such as the top-level concept *Problem*, need to be reorganized.

Hozo is available on the Internet (http://www.hozo.jp/), which partially satisfies the requirement for *availability*. The SS ontology residing on the server can be accessed by any user who has downloaded and installed Hozo, although a standard computing environment and knowledge of how to operate Hozo are necessary. *Availability* will be improved by preparing an exclusive website for the SS ontology.

Interpretability is fulfilled to the extent that the SS ontology and the mapping tool can help divergent thinking by explicating the knowledge structure. Using the ontology makes it easier to comprehend the differences as well as the commonalities between disciplines. For example, by comparing the maps generated from various viewpoints, a user could better understand the difference between his or her implicit assumptions and those of others. However, because interpretation depends on the particular mindset of each individual user, the ability of this function to achieve *interpretability* is limited. Helping users to introduce a new framework and interpret an issue along with the specific context is a function of Layer 3 in the reference model and will be addressed in a future study.

Value of the tool

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 users 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

[3] http://protege.stanford.edu/.

Table 2 Sample enquiries concerning *Problem* and *Countermeasure*

(1) What kinds of issues/options are there regarding the problem/countermeasure?
e.g., What kinds of issues are there regarding a global environmental problem?
What kinds of options are there regarding nature restoration?
(2) What is the problem's subject? Or, what is the target object or subject of the countermeasure?
e.g., What is the cause of deforestation?
What are the target objects of ecosystem conservation?
What kind of impact does supply shortage cause?
(3)-1 (inquiries for which a problem is a point of origin)
How and why does the problem occur?
<Which processes and factors are related to the problem?>
<Which action or cognition causes the problem?>
<Which incident or event is relevant to the problem?>
<How does the social system cause or affect the problem?>
e.g., How and why does deprivation of local culture occur?
(3)-2 (inquiries for which a countermeasure is a point of origin)
How is the countermeasure implemented?
<Which activity is needed to implement the countermeasure?>
<What kind of mechanism is applied to or involved in the countermeasure?>
<Which cognition facilitates or disturbs the implementation of the countermeasure?>
<What kind of social system facilitates or disturbs the implementation of the countermeasure?>
e.g., What agents facilitate the implementation of emissions trading?
(4) What are the inputs of the countermeasure?
<What is the material, social, or human resource of the countermeasure?>
e.g., What is the input of biofuel production?
(5) What kinds of things and/or subjects are related to the problem/countermeasure?
e.g., What kinds of things and subjects are related to eco industrial parks?
(6) Who are the stakeholders of the problem?
e.g., Who are the stakeholders of Transportation Demand Management?
(7)-1 (inquiries for which a problem is a point of origin)
What kinds of countermeasures or alternatives are available for solving the problem?
e.g., What kinds of countermeasures or alternatives are available for solving soil deterioration?
(7)-2 (inquiries for which a countermeasure is a point of origin)
What other problems could the countermeasure contribute to solving?
e.g., What other problems could the use of biomass contribute to solving?
(8) What problems must be solved before implementing the countermeasure?
<What new problems will implementing the countermeasure cause?>
e.g., What problems will using biomass cause?

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. In addition, we identify some missing concepts that we should add to the present ontology.

(i) Exploration using **Problem** as a focal point 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*'[4] 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 on the map to both *Hydroelectric power generation* as a *Process* and *Water pollution* as a *Problem*. Hydroelectric power generation is only a process utilizing water, and it is neither a target affected by water pollution

[4] In short, it means "show me sub concepts of *Problem* to two levels depth and such chains that eventually reach sub concepts of *Process* through *target*, *impact*, or *external cause*."

nor a factor causing water pollution. At least from these causal chains, it is not clear whether solving water pollution requires deliberation about what hydroelectric power generation should be. The reason for this is that the context of the causal chain changes when it reaches *Water*. We need to improve the expression of causal chains where such a switch occurs in order to represent it sufficiently.

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*’[5] 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.

As we noted earlier, the SS ontology used in the examples here is a preliminary version that does not have a sufficient number of concepts to fully represent SS. For this reason, the mapping tool cannot represent emerging issues such as the decline of agriculture, forestry, fishing, and traditional industries; food security; and invasive species. Enhancement of the SS ontology through the addition of concepts so that the mapping tool can represent such issues will be addressed in future research.

(ii) Exploration using *Countermeasure* as a focal point In addition to the points addressed above, we found several possibilities for improvements to the existing ontology and mapping tool in inquiries (4) and (8).

The mapping tool can visualize inquiry (4) using the command ‘*Countermeasure* (5 level depth) -implementing_actor|implemented_actor|implemented_target -> * <-*- *Process* <–input- *’.[6] In this map, many of the concepts’ attributes that are indicated as *input* are related to *Value of money*. *Value of money* is attached to many sub concepts of SS ontology due to the importance of investment for implementing countermeasures. In contrast, the current SS ontology does not contain relevant concepts of material resources and human resources. These concepts should be added to the ontology as class restrictions.

The mapping tool can visualize one facet of inquiry (8) using the command ‘*Countermeasure* (5 level depth) –byproduct-> *’.[7,8] However, the map generated by this command shows only a set of causal chains of the following form: *Countermeasure* –isa → *Present countermeasure* –isa → *System-based countermeasure* –isa → *Design* –isa → *Circulation process design* –isa → *Inverse Manufacturing* –byproduct → *Industrial waste*.

Relevant concepts of *byproduct* need to be added to the ontology and linked to sub concepts of *Problem* and *Countermeasure*.

Finally, the sub concepts of *Conversion of styles* should be improved. For instance, we should take into account media strategies, acceptance of foreign immigrants and different ethnic groups, and the introduction and expansion of telecommuting work style.

2. *Contribution to reframing*

Next, we examine how the tool can contribute to reframing users’ knowledge landscape. For example, a map using *Countermeasure* as a focal point can be generated by the command ‘*Countermeasure* (5 level depth) -implemented_target-> * <-*- *Object* (2 level depth) -input-> * <-*- *Process* -input|output -attribute-> * <-*- *Problem*’.[9] 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 –input → Ethanol –*→ Biofuel production –input → Corn –attribute → Food –*→ Starvation* and [B] *Countermeasure –isa → Present countermeasure –isa → Technology-*

[5] In short, it means “show me sub concepts of *Problem* and such chains that eventually reach sub concepts of *Object* through *target*, *impact*, or *external cause*.”

[6] In short, it means “show me sub concepts of *Countermeasure* and such chains that eventually reach *input*, a role that sub concepts of *Process* have through *implementing actor*, *targeted actor,* or *implemented target* relationships via *Process*.”

[7] In short, it means “show me sub concepts of *Countermeasure* and such chains that eventually reach concepts filling the role, *byproduct*, that sub concepts of *Process* have.”

[8] The concepts filling the role *byproduct* in this command are given in the definition of the concept *Inverse manufacturing*.

[9] In short, it means “show me sub concepts of *Countermeasure* and such chains that eventually reach sub concepts of *Problem* through *implemented target*, sub concepts of *Object*, its *input* (*fuel*), sub concepts of *Process*, its *input* or *output*, and its *Attribute*.”

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 a user to rethink his or her mindset or assumptions regarding starvation. We can learn three lessons from these kinds of conceptual chains.

First, the set of causal chains can assist 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 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 a user's thinking.

In this way, we can increase our understanding of the target object or problem and possibly 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.

Contribution to sustainability science

We now discuss how the reference model and the ontology-based mapping tool contribute to the solution of the challenges of SS that we identified in the "Introduction", namely, clarifying both 'what to solve' and 'how to solve.'

1. Contribution to identifying problems in sustainability science

As explained in "Trial use of the sustainability science ontology-based mapping tool", our mapping tool enables divergent exploration, which, in turn, redefines the 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 being dynamic is satisfied.

The reference model consists of raw data and an ontological base, exploratory concept mapping, contextualized convergent thinking, and a knowledge architecture for facilitating both divergent and convergent thinking. The reference model supplies a co-evolutionary function that promotes the 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.

2. Contribution to facilitating interdisciplinary research process

Layer 2 of the reference model is designed to identify cross-cutting linkages between diverse disciplines associated with SS through the divergent exploration in the conceptual world built at Layer 1. 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. We discuss the interface functions of the mapping tool according to these three aspects:

(a) *Links between concepts*. The mapping tool realizes the function of indicating links that interconnect relevant concepts, although the coverage of concepts is limited at this point and the appropriateness of each link should be examined in a future study.

(b) *Shared concepts of multiple disciplines* The concepts and links contained in our ontology are formulated so as to be sharable by many different disciplines. The commonness of concepts sometimes conflicts with the specificity of contents and contexts of individual problems. Emphasis on commonness may overly generalize the details of a sustainability issue; however, it is imperative to share some sort of common base for linking different disciplines, and an ontology provides such a foundational knowledge base. In addition, as described in "Trial use of the sustainability science ontology-based mapping tool", as long as divergent exploration is performed using such an interdisciplinary or 'domain-less' ontology, its results will not be constrained by any one discipline's boundary, which means that divergent exploration will result in cross-cutting inquiries.

(c) *Common theoretical meta-model*. As mentioned by Choucri (2007), different types of SS structuring have already been attempted. One of the advantages of the reference model is that it can work as a mediation device or common theoretical model of knowledge structuring with which researchers can compare relative positions and characteristics of each knowledge structure or tool. Such an interfacing function mediates different knowledge structures and also contributes to bridging multiple disciplines associated with SS.

In summary, we remark that the reference model can also contribute to the second challenge of SS of solving problems that inherently require interdisciplinary collaboration.

Conclusion

This paper addressed key challenges associated with knowledge structuring in sustainability science (SS), identified requirements for the structuring of knowledge, 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, as well as its usability, effectiveness, and constraints.

First, reusability, versatility, reproducibility, extensibility, availability, and interpretability were identified as requirements for SS knowledge structuring. Taking into account these requirements, we developed a reference model composed of five layers: Layer 0 stores raw data of the existing world, Layer 1 contains structured information and concepts in the form of an ontology to explain things and phenomena in the real world, Layer 2 enables divergent exploration by tracing multi-perspective conceptual chains, Layer 3 contextualizes the conceptual chains into multiple convergent chains, and Layer 4 helps an explorer understand or identify an essential problem for SS and assemble existing knowledge for its solution.

Second, we developed an ontology-based mapping tool as a tentative solution at Layer 2 of the reference model. The tool was designed to store and retrieve data and information regarding SS, to provide a prototype ontology for SS, and to create multiple maps of conceptual chains depending on a user's interests and perspectives. We discussed how these functions of the tool can contribute to the two major challenges for SS: clarifying 'what to solve' and 'how to solve.'

Third, we assessed whether the developed tool could realize the targeted requirements and whether it is complaint with the reference model for SS. Although several inappropriate causal chains remain in the prototype ontology and the concepts in the map cannot currently be distinguished by how they are classified in the ontology, the study concluded that the mapping tool can indeed facilitate divergent exploration, the function of Layer 2. The user experiment suggested that realization of the mapping of multi-perspective conceptual chains at Layer 2 could contribute to: (a) finding new potentials and risks of developing technological countermeasures to problems as demanded for SS, (b) helping users to envision a more comprehensive picture of problems and their solutions, and (c) helping to identify new ideas that might be missed without such a tool.

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 users' concerns. In addition, we are planning to develop functions for switching the targeted range of a chain as necessary, comparing multiple maps, and changing parts of a map interactively without requiring the user to input new commands.

Although discussion of the development process and quality of the SS ontology as a whole is beyond the scope of this paper, we have indicated some of the ways in which we should revise and improve the SS ontology. In addition to upgrading the SS ontology and the interface of the mapping tool, future work includes developing new tools to satisfy the functions described in Layers 3 and 4 of the reference model.

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