Artificial Intelligence and Sustainable Design — Papers from the AAAI 2011 Spring Symposium (SS-11-02)

Causal Knowledge Network Integration for Life Cycle Assessment

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Abstract

Sustainability requires emphasizing the importance of environmental causes and effects among design knowledge from heterogeneous stakeholders to make a sustainable decision. Recently, such causes and effects have been well developed in ontological representation, which has been challenged to generate and integrate multiple domain knowledge due to its domain specific characteristics. Moreover, it is too challengeable to represent heterogeneous, domain-specific design knowledge in a standardized way. Causal knowledge can meet the necessity of knowledge integration in domains. Therefore, this paper aims to develop a causal knowledge integration system with the authors' previous mathematical causal knowledge representation.

Introduction

Sustainable design requires multi-disciplinary design knowledge from various industrial domains to produce environment-friendly products. Sustainable design should consider life cycle costs from energy requirements and environmental impacts during manufacture and use phases, and material loss and environmental damage at the end of a product's life. Before the introduction of sustainability to the market, traditionally, an 'open-loop' based product manufacturing system has been developed and implemented, which considers product development, production, and distribution, excluding the consideration of process after use phases. In this open-loop based system, the boundary of design knowledge is restricted to a few industries that have been associated to manufacture a product. To fully enable reuse and recycle of a product by cradle-to-cradle design, however, sustainable design should be supported in the consideration of societal impacts of it. In other words, understanding of most industrial mutual causes and effects of products is imperative.

The challenges have been identified to analyze the causes and effects in practice for sustainable design: data collection, impact factor analysis, and integration for indicators (Rebitzer et al. 2004; Pennington et al. 2004; Reap et al. 2008a; Reap et al. 2008b). Especially, Life Cycle Assessment (LCA) is a methodological framework for assessing the environmental impacts attributing to the life cycle of a product (e.g., the CO2 level for measuring air pollution and the pH level for water) (Curran 2006). LCA practitioners first define the goal and scope and compile the life cycle inventory of emissions and resource consumptions associated with a product's life cycle. Then inventory data contributing to environmental impacts is assessed. These are highly time-consuming jobs with heavily intensive data in each industry. Once it has been successfully completed with data gathering and preliminary analysis of environmental impact exchanges (e.g., emissions, resource consumptions, etc.), it requires calculating and interpreting indicators of the potential impacts associated with such exchanges.

Furthermore, the solution might be no longer optimal for sustainable design, even though a company has a design solution of a product optimized in an open-loop based manufacturing system. The requirement of environmental impacts makes a new design problem in a closed-loop manufacturing system, which doesn't include the recycling and reuse phases. To implement sustainable design, the indicators of the potential environmental impacts should be incorporated with the sustainable design process. Unfortunately, the current indicators have been developed for the life cycle assessment of a specific domain based on ontological approach. However, current ontological indicators have been dependent on a specific domain, it is hardly to reuse, extend, and integrate them across domains. Therefore, the integration of such indicators across domains is important requirements for sustainable design.

In this paper, the domain-specific indicators of environmental causes and effects are represented in causal knowledge networks. This paper also aims to develop a system to support LCA practitioners with integrated causal knowledge based on the proposed network evaluation method. In the next section, we briefly review the current research efforts for knowledge representation in design and their challenges. The following section will discuss authors' previous work, causal knowledge network representation and the associated network evaluation method. Knowledge integration case based on the previous work is presented in the following section. In the end, the discussion with the future work will conclude this paper.

Background

Life Cycle Assessment

Life Cycle Assessment (LCA) has been ambitious to provide insights into the potential environmental effects of products and services. With the provision of products and services, it also has been in efforts to describe them as much complete. Hence the detailed system associated with the establishment of products and services has evolved into a powerful and robust methodological framework (Rebitzer et al. 2004). Such a comprehensive LCA approach is called a "detailed LCA" in comparison with simplified approaches (De Beaufort-Langeveld et al. 1997). According to the annual meeting of SETAC working group on data availability and uncertainty in LCA, for several applications, however, a detailed LCA study was not able to meet the possible benefit of the results in terms of the time and costs (Rebitzer et al. 2004). Concurrently, a concern rises "whether the LCA community has established a methodology that is, in fact, beyond the reach of most potential users" (Todd and Curran 1999). Hence, for the last decade, the challenge has been discussed to propose an overview of a system's impacts in order to decide on further investigations and has proposed frameworks such as ontological mechanism for product lifecycle (Rebitzer et al. 2004; Chen, Chen and Chu 2009). However, current ontological approach has been restricted to meet the demands of dynamic characteristics of LCA.

To analyze product lifecycle impact, the following challenging issues should be handled with the need to connect the right impacts at the correct time and place: impact category selection, spatial variation, local uniqueness, environmental dynamics, and decision time horizons (Reep et al. 2008b). Despite efforts to standardize several impact categories, currently standardization has been struggled and has caused difficulties of impact category selection (Udo de Haes et al. 2002). Due to a decade of awareness of spatial variation via multiple media (air, water, land) and local uniqueness, method development of the impact assessment is still an on-going research area. To identify site-generic, site-dependent, and site-specific LCA assessments, current research has been reported in no consideration of space (Potting and Hauschild 2006). To fully develop the assessments in terms of space, it is necessary to extend and integrate different environmental impact knowledge in different spaces. Furthermore, LCA is typically to exclude temporal information (ISO 2000). Udo de Haes stated that LCA is primarily a steady-state tool (Udo de Haes 2006). Unfortunately, by early 2000s, many researchers reported a real world that industrial and environmental dynamics affect impact assessment (Field, Kirchain, and Clark 2001; Graedel 1998; Owens 1997).

Knowledge integration in LCA

In the product design domain, the integration of heterogeneous product knowledge distributed among different collaborative enterprises is one of the most important research subjects suitable to knowledge management. Product lifecycles have identified the same issue to manage the distributed, heterogeneous environmental impacts. Many knowledge integration methods have been proposed (Bombardier et al. 2007; Gardner 2005; Bless, Klabjan, and Chang 2008; Ozman 2006).

Bombardier et al. (2007) developed a fuzzy algorithm based knowledge integration method with a symbolic model for representing knowledge and a tree structure for differentiating between different knowledge levels. In addition to the consideration of multiple knowledge levels, there has been in efforts to focus on an intermediary level to connect different knowledge sources to reduce associated joint management from all knowledge sources (Gardner 2005). Moreover, heuristic techniques and agent technology has been implemented to integrate knowledge bases (Bless, Klabjan, and Chang 2008; Ozman 2006). Such knowledge integration methods have primarily focused on integrating non-semantic knowledge or non-conceptual knowledge, and neglected to integrate all semantic or conceptual product knowledge. However, further effort is required to flexibly integrate heterogeneous environmental impact knowledge across various domains. Even though semantic knowledge integration is a necessary approach, current ontological approach to represent product lifecycle such as Chen and his colleagues' ontology mechanism is not enough to meet the aforementioned challenges for the needs of the dynamic integration among diverse knowledge since it should be defined every single instance of knowledge in tremendous costs and time.

Causal Knowledge Network

Causality has long been studied. The theory of the "Causal Calculus" permits one to infer interventional probabilities from conditional probabilities in the causal Bayesian networks with unmeasured variables (Pearl 2000). The complete causal network displays a consistent set of the direct and indirect qualitative dependencies, and preserves them as a stable part of the model, independent of the numerical estimates (conditional probability) of the causal strength. The representation allows domain experts to express directly and consistently the fundamental qualitative and intuitive relationship of the "direct dependency" between variable pairs (Lee and Alto 2001). The causal network (e.g., Bayesian belief network) has a sound mathematical foundation and reasoning capabilities; it also has an efficient evidence propagation mechanism and a proven track record in industry-scale applications. It is always essential but difficult to capture incomplete, partial, or uncertain product lifecycle knowledge. Hence the proposed mathematical representation shows how to define causal knowledge for product lifecycle impacts.

Mathematical Representation of Causal Knowledge

In the authors' previous work, we define causal knowledge networks mathematically in order to use the causal knowledge network (CKN) as a way to integrate design knowledge (Kim and Kim 2010). We adopt the definitions for causal knowledge networks for lifecycle assessment. The CKN is composed with the sets of vertices (*V*), edges (*E*), and weights (*W*) of the knowledge network. *V* is a set of all vertices in the knowledge network. E is a set of connected edges in the knowledge network, and W is a set of weights in the knowledge network. Figure 1 shows two types of the CKN, CKN_t and CKN_d: Definition 1 is for CKN_t, CKN with weighted vertices (e.g., Bayesian belief network); Definition 2 is for CKN_d, CKN with weighted edges (e.g., fuzzy cognitive map).

Definition 1. Causal knowledge with weighted vertices

The causal knowledge network is represented by $CKN_t = \{V, E, W\}$ as a weighted-directed graph.

Definition 2. Causal knowledge with weighted edges

The causal knowledge network is represented by $CKN_d = \{V, E, W\}$ as a weighted directed graph

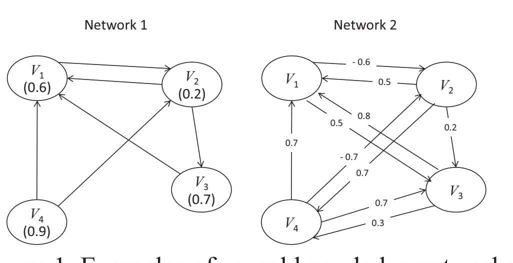


Figure 1. Examples of causal knowledge networks

Network 1 of Figure 1 is a CKN with weighted vertices and can be represented as follows:

$CKN_t = \{V, E, W\}$,
$V = \{v_1, v_2, v_3, v_4\}$,
$E = \{ e_{12}, e_{21}, e_{23}, e_{31}, e_{41}, e_{42}\}$,
$W = \{0.6, 0.2, 0.7, 0.9\}$

A CKN with weighted edges can be represented based on Definition 1 with modified weight (*W*). In this definition, the weights of the CKN_d are modified from w_l to w_{lm}, which means the weights are on the edges. Network 2 of Figure 1 is a CKN with weighted edges, which is represented by Definition 2.

$CKN_d = \{V, E, W\}$,
$V = \{v_1, v_2, v_3, v_4\}$,
$E = \{e_{12}, e_{13}, e_{21}, e_{23}, e_{24}, e_{31}, e_{34}, e_{41}, e_{42}, e_{43}\}$,
$W = \{-0.6, 0.5, 0.5, 0.2, 0.7, 0.8, 0.3, 0.7, -0.7, 0.7\}$

Knowledge Network Evaluation

Causal knowledge of environmental impacts of a product and the associated parts and processes can be represented in either the previous definitions. Then the causal knowledge should be evaluated at the level of network. After evaluating each network, we can compare multiple knowledge networks for the integration.

Degree of Causal Representation

As a consecutive result of the previous work, we define the degree of causal representation (DCR) as a causal representation measure (Kim and Kim 2010). The DCR_t is a combined measure with causality (*C*) and network connectivity (*NC*) for CKN_t, and the DCR_d is a measure with weighted network connectivity (*WNC*) for CKN_d. The corresponding definitions are following:

Definition 3. Causality

$C = \Sigma i\ (NP_i \times P_i)$

Causality is a measure how a CKN_t represents a causal relationship with the consideration of incoming and outgoing edges of each vertex.

Definition 4. Network Connectivity

$NC = \Sigma_{i,j}\ u_{ij}$

Definition 4 explains Network Connectivity. *NC* represents the connection of the network with the ratio of total connections in CKN_t. The ratio of total connections is an accumulation of each edge's ratio of connections based on the connection, which includes direct and indirect connection.

Definition 5. Weighted network connectivity

$$WNC_{ij} = \text{sum of } WNC \text{ for direct edge and indirect edges}$$
$$= u_{ij} \times e_{ij} \times p_{ij} + \textstyle\sum_{k1,k2}((u_{ik1} \times e_{ik1} \times p_{ik1}) \times (u_{k2j} \times e_{k2j} \times p_{k2j}))$$

$\times \quad {}_{k1,k2}(u_{k1k2} \times e_{k1k2} \times p_{k1k2})$

The DCR_d of CKN with weighted edges uses the weighted network connectivity (*WNC*) as shown in Definition 5. *WNC* is composed with network connectivity (*NC*) and the normalized edge weights of vertices.

Degree of Causal Representation Index

According to the causality and the network connectivity, causal knowledge network can be evaluated. The DCR, by the characteristic, is strongly reliant on the number of vertices in a network. In order to compare multiple causal knowledge with different number of vertices, therefore, it is required developing a normalization process. Hence, the proposed DCR index utilizes a normalization method for comparison of causal environmental impact knowledge with different number of vertices.

Definition 6. DCR Index

$I_{DCR} = (DCR_A - Min_{DCR}) \times 100 / (Max_{DCR} - Min_{DCR})$
, where DCR_A is actual DCR;
Min_{DCR} *and* Max_{DCR} are minimum and maximum DCR, respectively.

DCR is conducted with two parts, connectivity and probability, as defined in the previous section. The connectivity has more effect than the probability to calculate DCR. The number of vertices in the causal knowledge network is most effected parameter for calculating DCR. To develop DCR index, two cases should be defined (see Figure 2), minimum and maximum of each number of vertex. Each case has number of vertices, connectivity, and probability. For the minimum case, connectivity is minimum (only one connection between vertices) and probability is 0.51, which is lowest because there is no effect on 0.5 while 1 represents full effect. For the maximum case, connectivity is maximum (every vertices are connected) and probability is 0.99, which is highest in this paper.

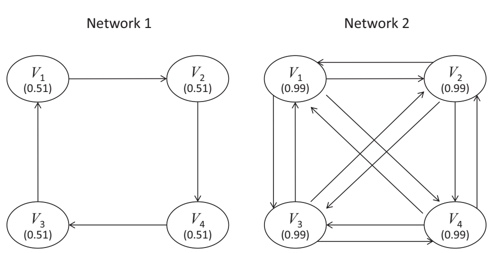


Figure 2. Examples of network for DCR

According to the DCR index, knowledge networks with different number of vertices can be compared in a normalized way. Figure 3 illustrates the proposed DCR index processing.

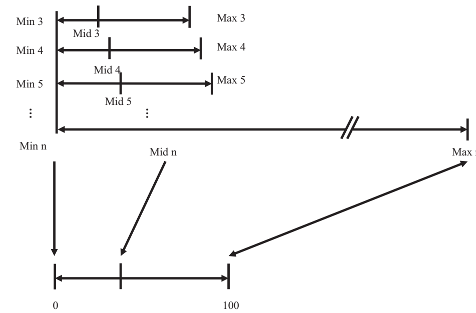


Figure 3. DCR indexing process

Based on DCR and the DCR index, knowledge networks will be compared for LCA practitioners to integrate to generate a combined knowledge network corresponding to the selected knowledge networks. In other words, the analysis of such knowledge networks for the integration will be guided by the causality, network connectivity, and the DCR index of the selected knowledge networks. For example, among two selected knowledge networks, if the DCR index of the first network represents higher value than the one of the second network while DCR of the first is less than the second one, then it explains that the first network has more degree of causal representation than the other one. By doing this evaluation, probability-based knowledge network can be prioritized since DCR and the DCR index can explain how much the knowledge network is able to represent the causality and connectivity. Based on this prioritization of integrated knowledge network, LCA practitioners could be recommended a knowledge network that can increase the representation in terms of causal relationship.

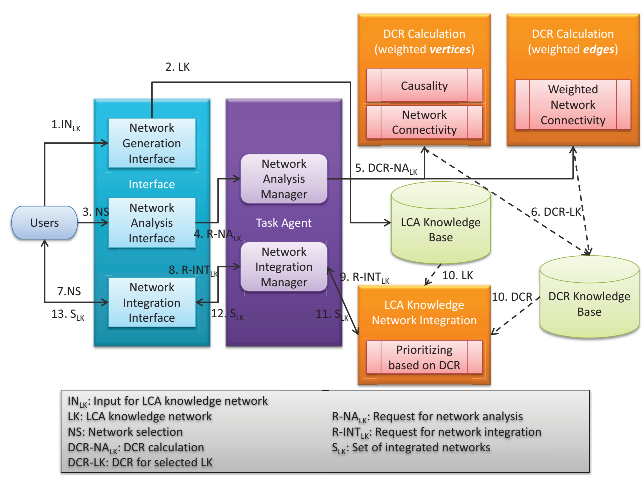


Figure 4. Architecture for DCR-based causal knowledge integration

Knowledge Network Integration

Knowledge integration is an intelligent knowledge acquisition method from existing knowledge. Based on inter-relational knowledge framework, knowledge integration includes three different cases (Figure 5). Case 1 is from inter-actor knowledge framework and is only belief integration in the same structure. Case 2 is from inter-process knowledge framework and is added the knowledge structures for integration and is updated belief between the structures. Case 3 is from inter-process knowledge and inter-product knowledge framework and integrates the knowledge structures and is integrated the knowledge structures and belief. The combination of these three cases can cover all possible integration cases in product development knowledge.

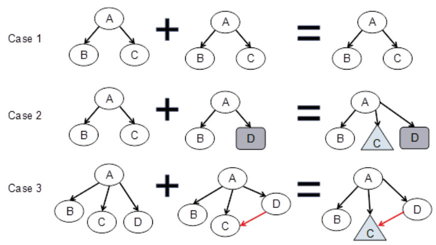
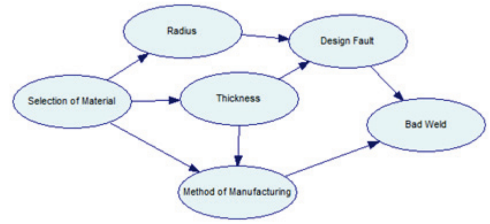


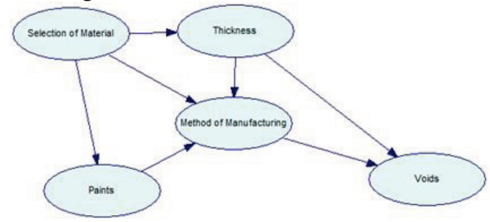
Figure 5. Knowledge integration cases

Based on knowledge integration cases, two main function is required, knowledge network identifier and integrator. The network identifier analyzes number of vertices, matching of vertices, structure of the knowledge network, and other considerable factors in knowledge. After analyzing the knowledge, network identifier can select the combination of knowledge integration cases (Figure 5). Based on the selected combination cases for knowledge integration, knowledge network integrator generates a new knowledge using structure and probability integration.

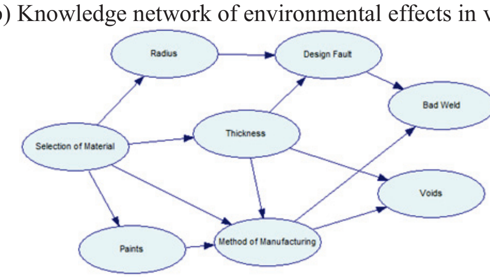
Causal knowledge integration method is utilized for a new product design using existing environmental impacts. In this case, the utilization of causal knowledge integration is presented with a wheel design scenario. A designer want to design a new designed automotive wheel, which is modified from existing design knowledge with constraints of environment impacts in different domains, i.e., welding and void, but current independent design knowledge is not enough to design the new wheel. Figure 6 shows this new wheel design scenario. Hence, the design knowledge integration is required. The designer opens web-based causal product design knowledge management system for sustainable lifecycles. Currently, the proposed knowledge integration system architecture has been developing.



(a) Knowledge network of environmental effects in welding



(b) Knowledge network of environmental effects in voids



(c) Example of integrated knowledge network

Figure 6. Knowledge networks for integration

Discussion

This research presents a general causal knowledge network representation model for lifecycle assessment. In addition, to compare LCA practitioners with knowledge networks, knowledge evaluation method is developed. Based on the proposed representation and evaluation methods, selected knowledge networks can be prioritized, which can recommend a knowledge network that can more powerfully analyze the combined network. The proposed system, however, is restricted to recommend knowledge network with more causality to LCA practitioners. Hence, for the future works, decision rule extraction method for LCA knowledge integration will be developed.

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