Engineering Design Education and Practice as Collaborative Knowledge Building

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Abstract

Engineering design is the process of devising a technical system to satisfy a defined need. The design process can be modeled as a transformation of knowledge. Collaborative engineering design can be described as a collaborative knowledge building (CKB) process. CKB is a goal-driven collaborative process of generating and refining ideas and concepts of value to the community. Properly applied and supported, CKB has the potential to improve both learning and design outcomes resulting from collaborative design projects. The paper proposes an integrated model of the CKB process, and discusses requirements for supporting computer tools. Existing computer tools do not provide adequate support for CKB, and better tools are needed based on the specific requirements discussed in this paper.

1 Introduction

A collaborative approach is required to find innovative engineering design solutions to increasingly complex and interdisciplinary socio-technical challenges facing society. Engineering design is “the process of devising a system, component, or process to meet desired needs. [1]” It is a process in which the basic sciences and engineering sciences are applied to convert resources optimally to meet a stated objective.

2 Engineering design as knowledge processing

The design process can be modeled as a transformation of knowledge [2]. The input knowledge is what is known at the beginning, and the output knowledge is what is learned about the solution. Sim and Duffy [3] surveyed the engineering design literature, and extracted a common set of generic activities involved in design process. These activities include synthesizing, abstracting, composing, defining, generating, analyzing, modeling, evaluating, deciding, etc. The activities are classified into three categories: design definition activities, design evaluation activities, and design management activities. Each activity can be described as a goal-directed knowledge transformation process. Input knowledge is existing design knowledge influenced by the tacit and explicit domain knowledge of the designers and the current design context. Output knowledge stems from specific design activity, based on the input knowledge, which is able to carry forward the design procedure to the final goal. It could be the solution to the original goal, a product configuration, product specification, and so on. An example of the transformation for the activity “analyse” is shown in Table 1.

Table 1. Knowledge transformation for "analyse" activity (adapted from [3]).

<table>
<thead>
<tr>
<th>Goal of design activity</th>
<th>Prediction of the behaviour of a design</th>
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Input knowledge

- The physical phenomena and theories
- The constraints, assumptions made and degree of accuracy required
- The structure/form of the design
- The working environment of the design
- Methods of analysis related to the physical phenomena

Output knowledge

Knowledge of the behaviour of the design

Knowledge change in design activity

Knowledge that a particular design in terms of form displays behaviour(s) that meets design criteria.

It is clear that new knowledge is created during design. Hicks et al. [4] describe knowledge creation as adaptation and extension of existing knowledge, combined with “inventive” activities.

### 3 Types of knowledge

Designers deal with three items: data, information and knowledge. Generally speaking, data are usually described to be textual, either in a numeric or alphabetical form, with insufficient context on their own. Information is the combination of text and data to describe a fact in an either subjective or objective way, sometimes unstructured. Knowledge is something “broader, deeper and richer” [5] than the former two, which is created from the data and information through human’s activities and then employed to solve problems.

It is useful to distinguish between explicit and tacit knowledge [3][6]. Explicit knowledge can be codified, communicated and shared. Examples include reports, standards, engineering drawings, mathematical formulas, catalogs, etc. Tacit knowledge exists in the minds of people, and cannot be easily accessed or communicated. Tacit knowledge can be classified as declarative (know what), procedural (know how) and causal (know why) [3]. Tacit knowledge includes skills, experience, mental models, personal understandings, beliefs, etc.

### 4 Collaborative engineering

Lu et al. [7] define collaborative engineering as “a new socio-technical discipline which facilitates the communal establishment of technical agreements among a team of interdisciplinary stakeholders, who work jointly toward a common goal with limited resources and conflicting interests”. They propose an Engineering Collaboration via Negotiation (ECN) process in which participants “employ a dynamic, socio-technical co-construction process to collaborate with each other reciprocally to reach participative joint decisions…[7]”. The emphasis of ECN is on sharing perspectives to reach a common understanding, followed by discourse and negotiation of individual preferences to reach a consensual agreement. According to this viewpoint, the fundamental task in design is decision-making.

It could be argued that the most important activity of design is idea generation, for without good ideas, decision-making is of limited value. The question now is how do groups collaborate to generate ideas and innovations, and how can we support this knowledge building process?

### 5 Collaborative knowledge building (CKB)

Nonaka proposed the SECI model of organizational knowledge creation [6]. The SECI model involves four modes of knowledge conversion: Socialization, Externalization, Internalization, and Combination. The socialization mode is defined as conversion of tacit knowledge to new tacit knowledge through social interactions and shared experience among organizational members, without language (e.g., apprenticeship). Externalization means converting tacit knowledge to new explicit knowledge (e.g., articulation of best practices or lessons learned). The combination mode involves the creation of new explicit knowledge by merging, categorizing, reclassifying, and synthesizing different individuals’ explicit knowledge (e.g., literature survey reports). Internalization means the creation of new tacit knowledge from explicit knowledge (e.g., the learning and understanding that results from reading or discussion).

An explicit framework for collaborative knowledge building (CKB) was developed by Scardamalia and Bereiter to support education and learning [8][9][10]. They define CKB as "the production and continual improvement of ideas of value to a community,"
through means that increase the likelihood that what
the community accomplishes will be greater than the
sum of individual contributions and part of broader
cultural efforts. Knowledge building, thus, goes on
throughout a knowledge society and is not limited to
education [9]." The focus of CKB is the construction of
shared knowledge artifacts through discourse aimed at
generating and improving ideas and concepts. It is a
deep constructive and dynamic improvement process
in which people advance the frontiers of knowledge in
their community through activities such as "identifying
problems of understanding, establishing and refining
goals based on progress, gathering information,
thorizing, designing experiments, answering questions
and improving theories, building models, monitoring
and evaluating progress, and reporting [9]". It is a
socio-cognitive process involving interplay between
personal tacit knowledge and shared community
knowledge. Scardamalia identifies twelve principles of
CKB as described below [8].

1. Real ideas and authentic problems. Knowledge problems arise from trying to understand the world, and to solve real problems. Ideas and concepts are treated as real objects in CKB.

2. Improvable ideas. All ideas and concepts are considered to be improvable. In CKB, ideas and concepts are shared, discussed, compared, connected, expanded, refined, etc.

3. Idea diversity. A diversity of ideas is essential in CKB. Ideas must be sought from many sources and perspectives.

4. Rise above. Higher level ideas, concepts and principles emerge from CKB through synthesis, abstraction, evaluation, comparison, classification, association, etc.

5. Epistemic agency. Participants are motivated and empowered to manage and direct their own participation in CKB, without being directed by teachers or other managers.

6. Community knowledge, collective responsibility. The shared goals of the CKB community are more important than the individual goals of the participants, and all participants share responsibility for reaching the community goals.

7. Democratizing knowledge. All participants are empowered to participate in CKB. Knowledge belongs to the community, not to individual members.

8. Symmetric knowledge advancement. Personal knowledge and learning advance in parallel with community learning. Participants learn from each other, and from engaging with ideas in CKB. Everyone contributes knowledge, and everyone learns.

9. Pervasive Knowledge building. CKB is not limited in time or space, but is pervasive.

10. Constructive uses of authoritative sources. CKB is built on a foundation of existing knowledge from authoritative sources. Participants identify and respect appropriate authoritative sources, and incorporate ideas from these sources. At the same time, participants evaluate sources critically.

11. Knowledge building discourse. CKB is more than sharing of knowledge, but involves creation of new knowledge and understanding through discourse. In CKB, the term discourse is taken to include discussion, debate, criticism, argumentation, negotiation and consensus-building.

12. Concurrent, embedded, and transformative assessment. Participants in a CKB community critically assess and evaluate their own progress toward the community goals. The purpose is to identify and address problems, issues and barriers to success.

Stahl [11][12] decomposes CKB into two interacting processes: personal understanding, and social knowledge building. Personal understanding evolves through a cycle of cognitive activities including:

- tacit understanding of the world
- experiencing breakdowns in understanding
- reinterpreting meaning structures to reconcile contradictions
- articulating ones understanding
- formally structuring knowledge

Group understanding evolves through a cycle of social knowledge building activities including:

- sharing perspectives
- exchanging arguments and rationale
- clarifying meanings
- negotiating conflicts
- formally structuring knowledge

Personal and social knowledge building cycles are mediated by tools including:

- Discussion tools
- Knowledge representations
- Physical, symbolic and cultural artifacts
- Personal external memory systems
- Shared group memory systems

Stahl’s model of CKB is very similar to Lu’s model [7], but with a focus on building knowledge rather than
making decisions. Stahl’s model is more complete, since decisions are also knowledge. Stahl’s model is not definitive, and continues to evolve. We propose a simplified model based on Stahl [12] and Singh et al. [13] as shown in Figure 1.

Figure 1. Integrated model of CKB.

This integrated model incorporates several important concepts, including:

- Representation of both personal and social knowledge building
- Representation of Nonoka’s modes of knowledge conversion between personal and social domains
- Sharing of perspectives
- Negotiation and discourse
- Reflection

6 Design, Learning and CKB

According to Scardamalia and Bereiter [9], “learning is an internal, unobservable process that results in changes in belief, attitude or skill. Knowledge building, by contrast, results in the creation or modification of public knowledge...”. However, according to Stahl’s model, personal understanding (learning) and social knowledge building are interdependent processes. From that perspective, any CKB activity produces learning. If we agree that engineering design is fundamentally a CKB process, then design and learning cannot be separated. Engineers are always learning. The difference between students and experts lies in the level of their personal frontiers of knowledge. Novice teams discover and construct knowledge that is new to them, but not new to experts.

Most student design teams do not naturally engage in CKB, and this is likely true in industry as well. Instead, most student projects involve only coordination of individual tasks, with little discourse. By effectively supporting CKB, both learning and design outcomes can be improved.

7 Computer support for CKB

Scardamalia and her colleagues have developed a software tool for CKB, called Knowledge Forum [10]. The fundamental objects in Knowledge Forum are ideas, which can be contributed, expanded, annotated, referenced, organized, synthesized and summarized. Ideas and their relationships are represented by a network of linked notes, which can be organized in
different ways through views. Knowledge Forum is used mostly in education.

Stahl [12] identifies several types of computer tools to support and mediate activities in CKB. These include tools for articulating ideas, representing personal perspectives, comparing perspectives, discussion and argumentation tools, glossary tools for shared meanings, negotiation support, etc. Based on Stahl’s CKB process and activities, we can identify some specific activities and requirements:

**Articulation tools to support conversion of tacit knowledge to explicit knowledge**

This is a common theme in the CKB literature. Most researchers limit articulation to putting thoughts into words. Engineers require much richer representations. For example, engineers articulate ideas using a mix of text, sketches, formulas, models, prototypes, etc. An articulation tool should support many information types.

**Sharing personal perspectives with the community**

Tools are needed to allow each participant to clearly outline their personal perspective or viewpoint, and share it with the community. Perspectives reflect personal ideas, values, priorities, beliefs, biases, preferences, knowledge, background, expertise, etc. Perspectives must be articulated so that they can be shared.

**Comparing perspectives**

Tools are needed to allow different perspectives to be compared and contrasted to identify areas of agreement, disagreement, conflict, contradiction, omission, etc. Personal perspectives evolve as a consequence of learning and social interaction.

**Clarify meanings and shared understanding**

Tools are needed to ensure that meanings are clear and understanding is shared. This could be supported by a shared glossary. For example, everyone should agree on the meaning of the words “perspective”, “discourse”, etc.

**Discourse, argumentation and negotiation**

Tools are needed to support discussion and argumentation around different perspectives, in order to reach a shared understanding and negotiate shared agreements. The perspectives themselves evolve as a consequence of discourse.

**Knowledge building**

Knowledge building requires tools to support linking, relating, classifying, abstracting, summarizing, filtering, etc. of many different ideas represented by documents, drawings, notes, comments, etc.

**Formalizing knowledge**

Tools are needed to formalize community knowledge. The formal representations include design reports, publications, engineering drawings, prototypes and designed artifacts.

Some additional requirements for computer supported CKB include:

- The system should be accessible anytime, anywhere to support pervasive CKB.
- The system should support both synchronous and asynchronous modes of interaction.
- The system should provide both private and shared community workspaces.

8 Existing computer tools

Existing computer collaboration tools have evolved without a clear understanding of the requirements of CKB. A key requirement that emerges is the need to structure and link diverse knowledge objects in complex ways. Collaborators attempt to use existing tools to support CKB, but with limited success.

Social networking tools like Facebook [14] provide rich social interaction capabilities, but little support for CKB. Shared workspace tools like Microsoft SharePoint [15] are very strong at managing documents and files, but have weak capabilities for creating knowledge structures. Wikis [16] permit text-centric collaborative knowledge building, but the discourse and structure are not readily visible. CAD tools focus mainly on geometry, and provide little support for collaboration, or for working with knowledge types other than CAD models and drawings.

We have evaluated Microsoft OneNote [17] as a collaboration tool to support the advisor/student collaboration between the authors of this paper. OneNote is a flexible and useful application for managing shared collaborative workspaces. OneNote uses a notebook metaphor, with information organized into pages in tabbed sections of a digital notebook. Many types of content can be embedded into the pages, including text, equations, diagrams, freehand sketches, freehand annotations, documents, links, screen shots, images, videos and audio clips. Objects on one page can be linked to other pages. Objects can be tagged, and searched.
A notebook can be shared by multiple users, who can edit it both synchronously and asynchronously. Changes are synchronized, and revisions are tracked.

While it is a very useful tool, the notebook metaphor does not support all of the requirements of CKB. In particular, it is difficult to generate alternative views of the knowledge structure, and links between objects are difficult to manage. It also provides no real argumentation or discourse tools.

Finally, OneNote is best suited to managing informal knowledge. Formalizing knowledge in the form of a paper or thesis requires transferring notebook content to another application like a word processor.

9 Conclusions

Collaborative knowledge building (CKB) has emerged as a leading theory in education and learning, and can be applied in any context including engineering design. The fundamental idea of CKB is that participants collaboratively construct knowledge by generating and improving ideas and concepts. CKB promotes deep learning.

Outcomes in both design education and design practice can be improved by promoting a CKB approach. CKB does not happen naturally in every group, so tools and supports are required.

Existing software tools to support collaboration provide only weak support for CKB. We need to identify the requirements, and develop tools to better support CKB.

10 References