A Concept Map-based Cognitive Framework for Acquiring Expert Knowledge in Industrial Environment

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***Abstract*—Preserving important troubleshooting experience gained in industrial practice, often referred to as "tribal knowledge", and making it readily available to be re-applied in similar situations represent a serious challenge for many companies in heavy industry. The solution is very often tied to building mental models to capture and express key latent cognitive variables. In this paper, we first attempt to identify the appropriate knowledge-based system diagnosis paradigms. A conceptual map-based framework is then proposed as a potential solution for retaining tribal knowledge. The validity and feasibility of the approach are demonstrated through a training program developed under the support of National Science Foundation (NSF) for improving engineering and technology students' troubleshooting skills.**

I. Introduction

Knowledge-based system diagnosis has been a very active research area in the last several decades [1]–[3]. It focuses on capturing expert knowledge with the ultimate goal of using the knowledge for practical problem solving. The evolution of this field has progressed to the phase of formulating troubleshooting as a collaborative activity between humans and computers where computers help elicit mental models and analyze results. However, for cognitively motivated computing tools to provide more effective assistance, we first need to have a better understanding of human diagnostic problem solving.

Studies in cognitive psychology have shown that internal representation of knowledge is organized and structured in a web or network fashion where more connections usually lead to better understanding. When individuals need to retrieve pertinent information to perform domain specific tasks, the more integrated structure of the mental model is, the more efficient the knowledge can be used [4]. The general homogeneity of field experts' models and their variance from novices' models indicate that models can differentiate disparate levels of comprehension [5]. Therefore, externalizing internal conceptual understandings not only can shed light on an expert's thought process for problem solving, but also let beginners to use the discrepancy between their conceptualization and expert's to achieve better learning outcome. These findings and cognitively motivated tools designed based on them, have been deployed to classrooms at different levels to help improve student learning, and the underlying mechanism has shown some promises in displaying and communicating information, instructional material design, supporting instructional activity, and assessment, *etc*. [5]–[7].

In addition to classroom teaching and learning, another area where forming cognitive models, or more specifically conceptualizing relationships among a task's components, can be extremely valuable is retaining expert knowledge in industrial environment, commonly referred to "tribal knowledge". Generally, tribal knowledge is not some routine knowledge known to a mass audience, but rather special expertise procured through experience by only a handful of employees. These employees are usually senior personnel in the quality, maintenance, or control department in the organization, who have acquired expertise on a equipment, system, or process over an extended period of time, sometimes decades. To capture and transform this unique expertise into the company's own knowledge base, or even intellectual property, is critical for the company's sustainable growth.

The importance of tribal knowledge and the severe consequence of its loss caught our attention when we participated in the I-Corps L program sponsored by the National Science Foundation and American Society for Engineering Education in 2015. During the customer discovery phase, our team interviewed over 100 potential clients, the majority of whom were engineers, managers and directors of operations in heavy industry like energy, manufacturing, and health care. Tribal knowledge emerged as the most talked-about issue in these dialogs and it became obvious that providing a plausible solution required a new, innovative approach.

Several feedback from the customer discovery stand out. On one hand, the formal practice for recording tribal knowledge in almost every company is internal reports. It is widely considered to be ineffective and difficult to retrieve. And during the on-site one-on-one shadowing, which is the occasion for preserving tribal knowledge informally, veteran engineers normally do not have the luxury to explain the thought process

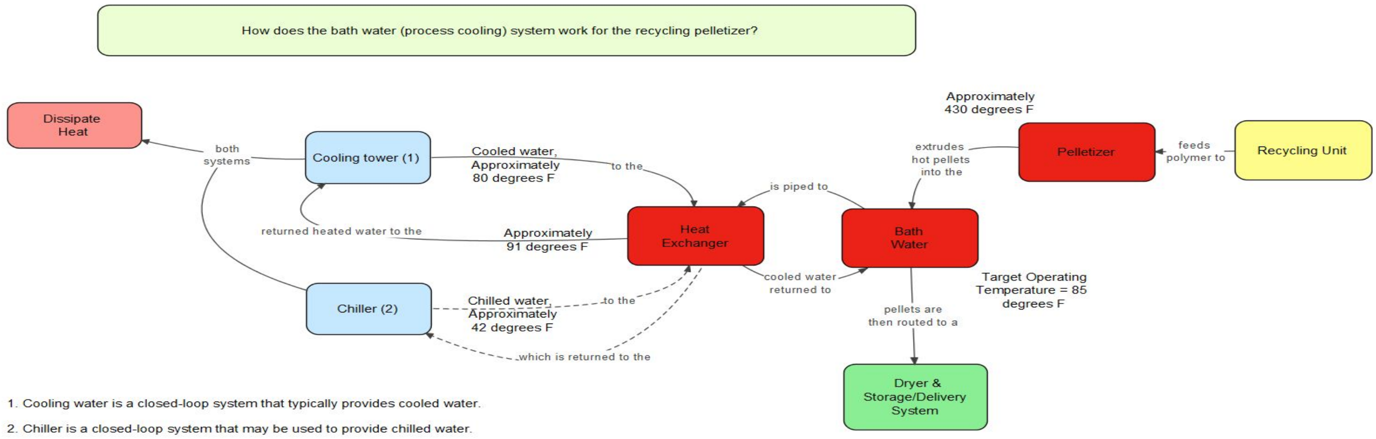

Fig. 1. Expert's Map for Heat Exchanger Problem

thoroughly to new employees during maintenance checkup and malfunction diagnosis. On the other hand, all young engineers emphasize that they are more of the "visual learner" type. They absorb and grasp domain knowledge better when they can see a picture of the overall system. We feel that the root for tribal knowledge dilemma, whether it be finding effective tool to elicit information or helping the learners get the visual representation of problem solving, can be traced to communication through the mental models between the experienced and inexperienced personnel.

Over the years several studies have been attempted to mitigate the problem. For instance, in [8], a form of constraint propagation within the distributed cognitive system was used to support the dissemination of tribal knowledge in the aerospace industry. Dennehy *et al.* presented a simple approach called "Pause and Learn" as a low-impact method of organizational learning that could foster the timely capture of critical lessons learned [9]. However, these tools either focused on sharing rather than documenting knowledge, or did not provide a mechanism to preserve knowledge cohesively and intuitively to make its inheritance easier and faster.

Conceptual mapping is a well-recognized approach that uses both content knowledge and process knowledge to prompt users to create visual maps of a diagnostic strategy to identify technical problems in complex technical systems. In this paper, we propose and demonstrate a concept mapping-based framework that helps archive tribal knowledge and provide more agile training tools for new employees.

II. Methods

Engineers and technicians have long used decision-trees or trouble-shooting guides to assist the diagnostic process while identifying problems in technical systems. However, a prominent element of semantic memory theory is associative networks of knowledge, whose central premise is that knowledge is stored in a network format where concepts are connected to each other. The more tightly interconnected the knowledge representation, the more likely it is that a person will recall information at the appropriate time [7]. Based on this conclusion, it is readily conceivable that the tool to capture tribal knowledge should include graphical schematic of experts' perception of the task's components, their cognitive organization of the routine elements, and the relationships between these elements [10].

For this reason, we have chosen concept mapping developed by Novak [11]. Interest in concept maps stems from their relationship to memory and learning theory. Although oftentime a complicated and time-consuming knowledge acquisition process, conceptual mapping is nonetheless a good tool to portray knowledge structure and to diagnose learner's misconception in learning. It has been used in the development of agile diagnostic thinking skills of students who have limited content expertise [5]–[7], [12]. For instance, in [13] the algorithm of Apriori for Concept Map was applied to develop an intelligent concept diagnostic system (ICDS) to provide teachers with learners' constructed concept maps and enable teachers to diagnose the learning barriers and misconception of learners instantly. Conceptual mapping has also been used in psychology [14], computer programming [15], and problem-based medical curriculum [16].

When using concept maps for diagnostic skills training and helping trainees in learning critical knowledge, we need to establish a proper mechanism to assess the quality of learning, or in another word, generating valuable feedback to help learners improve by comparing concept maps from different sources. Unfortunately, it has been recognized that the major obstacle for conceptual mapping to gain more traction is the lack of efficient evaluation tools. Different techniques have been proposed to automate the process. What these methods have overlooked however, is the fact that maps contain nodes and links, and consequently not only the content of, but also the relationships between nodes are important. An effective evaluation strategy should take advantage of the wealth of information embedded in this topological structure.

A weighted mechanism was proposed in [17] where each proposition was given a weight value between 0 to 1. The

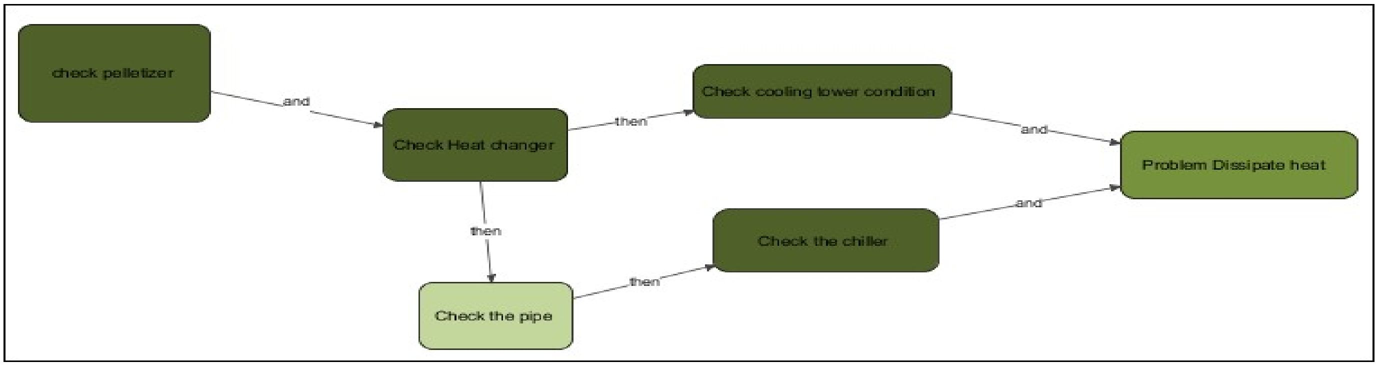

Fig. 2. Student's First Map

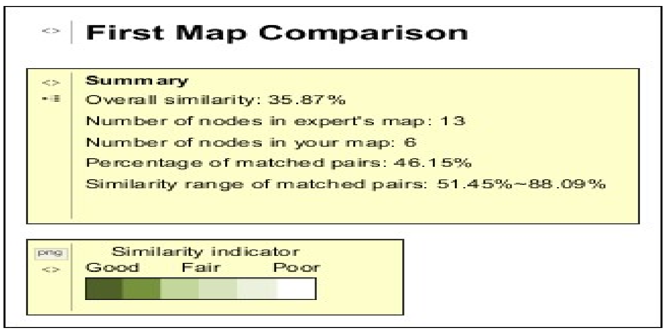

Fig. 3. Summary of the First Comparison

higher the weight, the more important the proposition was. By comparing a student's map with a teacher's (expert's) map, each node in both maps received a closeness index. Each node's similarity index is then calculated based on its closeness index and weight. Using the similarity index, learner's comprehension of the node could be ranked into "learned", "partially learned", or "misconception" [17]. The limitation of this method is that the nodes in the concept maps are predefined, and students use predefined concepts and links to construct their maps, so the content of the nodes and links are not considered as a factor in comparison. The maps in our training software are open-ended maps, so the algorithm based on closeness index and similarity index is not applicable. However, the weighting mechanism is still helpful to identify the importance of nodes in the expert's map.

Another method called Similarity Flooding Algorithm (SFA) was presented in [18]. SFA took two graphs as inputs, and matched the nodes in both maps. The similarity relied on the intuition that nodes from two maps were similar when their neighbor nodes were similar. The output was a list of corresponding nodes, each with a similarity value. After a filter selection, the most optimized pairs were considered as the best matched nodes. SFA works on many types of graphs such as data schemas, catalogs, eXtensible Markup Language (XML) ontologies, to name a few. Particularly, SFA supports open-ended nodes and directed labeled graphs, for instance, a process map which has arrows on links between nodes to indicate the order of the steps of a diagnosis strategy.

Other than the nodes, another critical comparison has to be made in regards to the links. In [19], an approach of string comparison with the meaning of the words– semantic similarity was proposed. The approach used WordNet-based Semantic Similarity Measurement (WSSM) as the database for synonyms. WordNet is a database and an open source project based at Princeton University. We used five steps to compute a semantic similarity for two sentences. The steps are (a) separating sentence into a list of tokens, (b) disambiguating parts-of-speech, (c) stemming words, (d) finding the most appropriate sense, and (e) computing the similarity. Although there might be many limitations, the method worked fine for this research because the target learners were supposed to be trained to use terms in their maps.

Our method of comparing concept maps is based on combining the weighting mechanism, SFA, and semantic similarity of two strings. We used an implementation of SFA developed in [18] (Open source Java program to convert Java code to C#) to match the nodes based on their relationships. The SFA represented two input maps semantically in code first, then created an initial map for the product of each node in both maps, calculated their similarities based on the links, and finally generated a list of best paired nodes according to the similarity of each pair. During the comparison, WordNet was used to measure node contents.

III. Results

In this section, we demonstrate the validity of concept map-based framework using the outcome of a practical project. We present a concept map developed for troubleshooting heat exchanger in waste plastic pelletizers. It was a collaborative effort between Beamis, a packaging solution company at Terre Haute, Indiana and an Indiana State University team who was supported by the National Science Foundation to develop training software to improve diagnostic skills for undergraduate engineering and technology students.

The problem is: the water bath system was malfunctioning and there were multiple reasons that could have caused the problem. The task is to develop a process map to diagnose the root cause(s) of the problem. We first show the acquisition

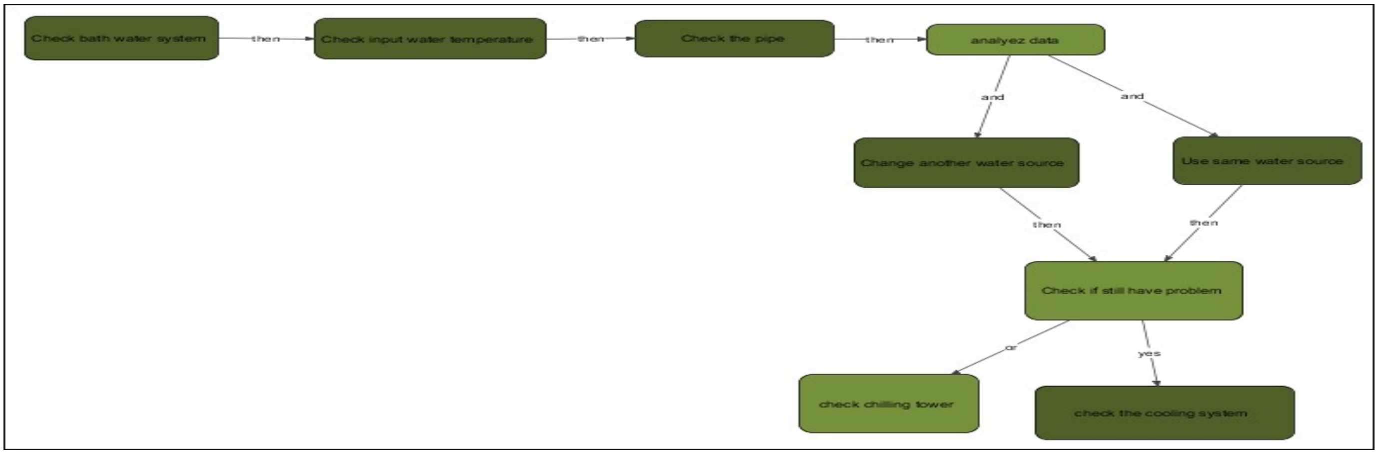

Fig. 4. Student's Second Map

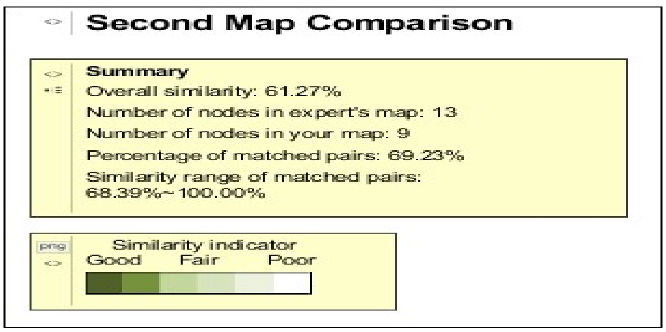

Fig. 5. Summary of the Second Comparison

of expert's tribal knowledge using concept map. Then, we illustrate the use of preserved knowledge to help students who have limited background on this specific task to gain more experience by undergoing the training program.

Fig. 1 shows the concept map conjured by an expert that detailed the diagnosis thought process in a systematic way. Student created their own maps using Visual Understanding Environment (VUE) concept mapping software (an open source project developed by Tufts University; http://vue.tufts.edu) within an instructional shell created in Lectora. One of these maps is shown in Fig. 3. The deep or light green color indicates node's closeness to its counterpart in expert's map. Comparison of maps is summarized in Fig. 2, where it shows a 36% overall similarity and 46% of nodes had considerable similarities to the expert's map (range from 51% to 88%). The main separation is caused by the fact that the student's map has only six nodes while the expert's map has13 nodes.

After reviewing feedback provided by the comparison program, the student made changes accordingly and completed a second map which is shown in Fig. 4. The new map contains three additional nodes that are similar to those in the expert's map. The comparison summary (Fig. 5) indicates the overall similarity is increased by 25% (from 36% to 61%) and the matched nodes are increased by 23% (from 46% to 69%). The highest similarity of an individual node, "Check input water temperature", is 100%.

IV. Discussion

During the course of the NSF I-Corps L program, we engaged in an intensive exploration of opportunities to commercialize prior NSF TUES project on improving diagnostic skills for engineering and technology students [20]. We discovered that the loss of tribal knowledge could pose very serious problem to many companies, but was particularly detrimental to small businesses. Compared to their corporate counterparts, these companies cannot afford to prioritize addressing tribal knowledge problem. On one hand, they lack a rigorous process based on established quality standard such as ISO-9000 to document and maintain the information systematically. On the other hand, the companies usually do not have in place a good succession plan or training program for new workers. Therefore, if one senior employee whose working knowledge has not been properly retained leaves the company, the loss of expertise can affect the entire business/manufacturing operation; and sometimes it can lead to even more severe consequences.

In this paper, we propose a concept map based framework to help business, especially the heavy industry to retain domain specific tribal knowledge. We feel that our approach should be particularly appealing to small businesses due to the following features. First, the software uses primarily open source resources, which makes its development cost affordable. Second, the software can be developed in stages. Each module is independent and can be used to capture a specific tribal knowledge subject. This allows small companies that have to delay implementing any plan on tribal knowledge due to budget constraint to capture the most important working expertise first, and gradually build up their own knowledge base. We believe there exists a huge potential for this program to function as an interactive, stand-alone tool for archiving tribal knowledge and training new employees in industrial environment.

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