Concept Maps as a Tool for Engineering Education
Zoja Raud and Tõnu Lehtla
Tallinn University of Technology (Estonia)
zoja.raud@ttu.ee

Abstract — Concept map application in engineering education is described. An effective role of concept mapping in the overall knowledge domain ontology is stressed. It is shown that the concept maps are a suitable tool to support teachers in promoting students’ comprehension of learning material contents and improving their understanding of new concepts. Development of concept maps helps students to see what they have acquired from the classes, supports them in making connections between new and prior concepts, and reinforces knowledge integration by providing students with an activity that promotes such integration. Concept maps are regarded as a valuable tool of assessment procedures, as they provide an explicit and overt representation of learners’ knowledge, informative, tutoring and reflective feedbacks tailored to learners’ individual characteristics and needs.

I. INTRODUCTION

Educators often expect students to find connections between the concepts they teach in a course, and between topics they teach across the courses in the curriculum. In so doing, teachers rely on the novel educational technologies, such as databases, learning portals, webinars, tutorials, Web, and social networks that enable students to access large amounts of learning materials. As a result, the teachers are often disappointed when students have failed to make expected connections for themselves, as they disregard the fact that high knowledge proliferation often leads learners to a serious problem that is called information overload [1]. Working without assistance, the students come across scrappy and fragmentary data, frequently resulting in disorientation and inability to construct complete and systematic domain knowledge.

Many researchers concentrate on the methods of increased appreciation for large volumes of information. Traditional curricula management has become inappropriate both for educators and learners who need continuous enhancing of their professional knowledge. To overcome such restrictions, some novel approaches have been developed in the worldwide educational practice. Particularly, a “curriculum container system” was proposed in [2]. This five-level structure with the curriculum, unit, task, episode, and element levels is rather complex for teachers who should follow it carefully along with the learning process. The teacher’s activity is limited here by the curriculum “aggregates”, thus any time when somebody wants to change a learning trajectory, the curriculum is to be modified. Another tool for learning improvement is a knowledge representative “conceptual graph” [3], though this approach elaborates the storing technique that has strong influence on the syllabi content rather than on the curriculum topology.

Studies [4], [5] have emphasized how the presence of signals like titles, headings, previews, overviews, summaries, typographical cues, recall sentences, number signs, important indicators, and summary indicators in texts and lessons affects subsequent memory for understanding. Virtually all types of signals produce better storing for information they cue, whereas memory for “unsigned” information often is unaffected. Observation of [4] has indicated that top-level organization of learning material and culturally familiar context significantly increase the amount of knowledge that students can recall and their overall high comprehension. Research [1] has suggested that graphical representation of studying material can reduce the problems of information overload and disorientation for learners.

One of the most powerful graphical tools refers to concept mapping. It was shown in [6] that concept maps can scaffold learners to understand new topics by mapping the relations among new topics and learned domains. Basing on the concept maps, this paper aims to show tools intended for achieving flexibility in learning, to provide instructors techniques for further improvement and refining of the teaching strategies. The first part of the paper presents a methodology composed of the identification of relevant concepts in multiple sources of knowledge, design of concept maps, and storing of the multi-disciplinary learning objects linked to these concepts. Concept maps were selected here as an instrument that can help students in understanding the engineering knowledge domains and in making connections among the concepts. In the following parts, the concept maps are used as an effective tool to elicit a student’s understanding of studied topics both before and after instruction. They demonstrate how the status of a particular concept can possibly be influenced by learning statuses of other concepts, thus giving learners an adaptive guidance for understanding the course material.

II. ONTOLOGY OF KNOWLEDGE DOMAINS

Any discipline of an educational curriculum can be presented from an ontology perspective as a knowledge domain. A description of the concepts and relationships to enable knowledge sharing and reuse is known as ontology [7]. Ontology formally represents knowledge as a set of concepts within a scientific domain, and the relationships among those concepts. Usually instructors use ontology created by authorities in the required field of science (domain experts) to design a syllabus in a way that reduces information overload and learning disorientation. Besides, instructors also use ontology to prepare teaching materials and to design learning paths for students’ guiding [8].

To display ontologies and to transmit them from a teacher to a learner, a model is needed that would provide an abstract, formalized, and simplified image of a phenomenon and its interactions. Commonly, three types of models are discussed in science, namely, mathematical models, descriptive models, and graphic models [9]. Effective descriptive models were developed in [10], [11] in the form of educational thesauri.
Graphic models apply diagrams and symbols to illustrate simple and complex relationships. Concept maps, first suggested in [12], were defined by Joseph Novak as “graphical representations of knowledge that are comprised of concepts and the relationships between them”. Putting it simply, concept maps are graphical representations of the hierarchy of knowledge concepts and connections between them [13]. Concept maps have their origin in constructivism which explains how to keep prior knowledge as a framework to learn new knowledge. From the educational perspective, constructivist learning theory states that a learner attains new knowledge through a process of integrating new knowledge with existing one [15]. Novak’s work was based on the assimilation methodology of David Ausubel, who stressed the importance of prior knowledge in being able to learn about new concepts. In [14], [16] concept mapping was shown as a first step in ontology development which, following [17], can also be used flexibly to represent a knowledge structure for the first step in ontology development which, following [17], can also be used flexibly to represent a knowledge structure for meaningful learning along with the educational thesauri. An interest in concept mapping stems from its interconnection with both the memory theory and the learning science [18]. A prominent state of the semantic memory theory relies on associative networks of knowledge. The central premise is that knowledge is stored in a network format by interconnecting the concepts. The more tightly the knowledge representation is linked, the more likely it is that a learner will recall information at the appropriate time. Therefore, a network representation shows the integration of different concepts. These theoretical bases have resulted in practical approaches used in concept maps including semantic networks and knowledge maps.

The purpose of this paper is to review the use of concept maps in engineering education. To compare and evaluate multiple reviewed approaches, the authors produced their own graphical knowledge models represented as a set of concept maps and associated resources of a science domain. One of the most popular concept mapping instruments is CMAP Tools. This software environment developed at the Institute for Human and Machine Cognition (IHMC) empowers students, individually or collaboratively, to represent their knowledge and to share them with peers and colleagues. To be available for free for educational use, IHMC established the net of public servers that promote the sharing of knowledge. The client-server architecture of CMAP Tools allows publishing of the knowledge models in Concept Map servers, and enables concept maps to be linked to related maps and to other types of media, such as images, videos, Web pages, etc. Also, CMAP facilitates publishing through the Web by automatically converting the concept maps to HTML files, which can be browsed immediately using an Internet [19]. Today, CmapTools are important applications of engineering activity because of their focus on procedural knowledge and product interface design. Overall patterns in concept maps were found indicative of cognitive status. At the same time, many other concept-based graphic tools are identical but differ in the way they focus on object identities, conceptual relationships, and their structural and functional roles.

Since the concept maps appeared, their use has facilitated many educational problems. They were applied in a variety of fields, including instruction, learning, curriculum development, and assessment. Concept mapping is used in mechanical, chemical, and computer engineering across a wide range of educational applications [20]. The constructed concept maps can provide a useful reference for beginners, for teachers to design adaptive courses, and for learners to understand the whole picture of the studied knowledge domain. Researchers use concept maps to communicate and to support the design of materials. Others have focused on the of concept map construction as an instructional activity.

In the recent years, many studies in educational sciences have changed the role of concept mapping, shifting it from a tool for supporting an individual learner to a tool for promoting collaborative learning [21]. The former tool supports the structure of knowledge owned by an individual student, thereby helping the teacher or learner to detect errors in the acquired knowledge or in linking together acquired and new concepts. The latter instrument, on the other hand, supports dialogues between a learner and among learners, which is useful to deepen domain understanding. Some researchers, for example [22], have found how collaborative concept mapping improves students’ interaction and allows them to learn about their classmates. Different ways were found to generate common knowledge and to share information depending on the learning domain, the collaborative techniques implemented to organize the activities [23], the type and place of interaction (synchronous, asynchronous or both), the method of management [24], and finally, the available platforms for work and collaboration. The remote users can collaborate asynchronously or synchronously in the map design, promoting comments, criticism, and peer review. Using this technique, students can publish their maps whereas others can comment them and provide other feedback.

III. CONCEPT MAPS AS A TEACHER TOOL

Following Novak’s rules [25], the described approach applied to teaching should result in providing accurate information about the knowledge domains studied. First, the maps developed must include concepts linked by linking words that form propositions. Next, they must also have a proper topology at which more general concepts should be higher in the map, and more specific concepts should occupy lower levels. Concepts within the same level of generalization should be on the same level of the topology. Therefore, the outcome of concept mapping comprises concepts, relationships, and a topology.

The procedure of knowledge transfer was divided in [1] between four main steps:

- information retrieval
- concept extraction
- search for the key concepts
- evaluation of “relation strength”

Accordingly, before constructing a concept map for a domain, the teacher distinguishes between content covered through lecturing and concepts provided through labs, exercises, and other studies. Additionally, such sources of information as textbooks, scientific and popular books, and Web sites supply the students with information also. To
provide successful concept extraction, it is healthy to collect the terms in an educational thesaurus. The concepts proposed by different authors are not always consistent, as the authors may describe the same concepts using similar terms but not exactly the same ones. Therefore, the terms must be classified by instructors into appropriate groups to reduce the total number of concepts. A thesaurus created to store these grouped terms is a very useful tool from an educational viewpoint. Today, few educational thesauri are known, hence the samples from [26], [27], [28] may be considered as unique and valuable. The educator’s purpose is to summarize large datasets to remove data redundancy and to find the key concepts. Then, the evaluation of concept “relation strength” must be decided. In the simplest case, a linear topology without loops and with minimal concept linking can be proposed. However, many concepts have complex interconnection and, on the contrary, some concepts have no links with other concepts within the domain. Such decoupling should be minimized in the learning process by the teachers or through the peer-to-peer communication.

Following Novak’s definition, a focus question of the particular lesson should require no more than 25 concepts. This demand affects concept mapping with minimal redundancy and minimal loss of information. Therefore, simplicity is the first important instructor’s requirement. If a concept set is too large, several concept maps can be used. In the same way, summaries are created for a chapter and for a part of the studied domain.

Concept maps of different instructors are subjective, because every concept map represents the author’s knowledge and skills. In an educational context, a teacher wants to infer the student’s understanding and perspective on a topic. The educator also wants that terminology used by the student would enable assessment of the outcomes, so the concept maps should be represented by different resources in the same way, i.e. using the same words. This requirement affects concept mapping in two ways:

- the words for the concepts and relations must be extracted from a common basic dictionary
- the hierarchy of concepts must reflect the importance of the concepts presented in the particular domain

Based on the above given regulations, the major task when creating a concept map that describes a sub-domain is to discriminate the most meaningful concepts from the less important ones to make them the basis of the concept map created. Thus, the first step taken by the instructor is to determine which concepts are most essential, those that the student should not obviate. The second step of a concept map creation is to link the concepts involved to construct a meaningful information structure. Thus, a network is designed consisting of concept nodes (points, vertices) and links (arcs, edges) that provide the relations among concepts, such as, “is a”, “related to”, or “part of”. Besides these two steps, there are other quality details that appeal the map designer’s dedication and interest in creating the concept map, including segregating of the most important concepts from the rest through highlighting (fonts, colours, shapes, etc.), representative icons and figures, and connecting to outside Web pages, applications, or other concept maps. A

The concept maps also includes cross-links that display relationships between concepts of different domains. Cross-links show how a concept in one domain of knowledge shown on the map is related to a concept in another domain.

The concept maps developed in accordance with the described rules are a suitable tool to support teachers in promoting students’ comprehension of the contents of a learning material and improving their understanding of new concepts.

IV. CONCEPT MAPS AS A STUDENT TOOL

The aim of concept mapping for learners is to interpret learners’ personal understanding and their possibilities to draw individual examples against the existing theoretical and practical tasks. Being a flexible tool to focus attention on important aspects of knowing, the concept maps help to explore what students are actually learning and how they do it.

Mapping process demonstrates what learners see as important concepts and how they relate these concepts. The results of mapping can have implications for clarifying the learning objectives, refining instructional strategies, identifying appropriate assessment tools, and understanding how the learning objectives are being realized by students. According to [29], the concept maps allow students

- to develop a flexible structure for self-directed learning
- to manage large amounts of information in the knowledge base which they build in the learning process
- to track personal progress in various areas and aspects
- to share their maps with others for feedback or evaluation
- to facilitate setting up the personal learning goals

Concept maps are generally used for learning purposes in two ways:

- students build their concept maps following a focus topic
- students analyze preliminarily designed concept maps (usually instructor-built)

Both approaches have been found to be effective instruments to improve students’ learning outcomes. The maps are created over time by the learner engaged in a process of reflection, collecting and selecting appropriate knowledge.

When concept maps are designed in the classroom, mapping time is usually restricted by 5 to 20 minutes [30]. On the contrary, if mapping specifies their homework, learners will have a lot of information from numerous sources, such as books, Internet, and other digital media libraries. The contents of these sources can be useful to appreciate the course or to simplify knowledge understanding. Otherwise, it is not a trivial job for students to organize and identify the main thematic topics. Therefore, students force multiple learning objects and make notes in their concept maps to personalize learning and to re-enforce it for increasing skills and promising the knowledge sharing.
The hierarchical nature of the concept map allows for organizing concepts from the high abstract level to more specific layers. This property can be used by students for managing and structuring data. Following the qualitative analysis techniques, students create their own relations for the concepts which later form their personal concept maps. Students can also be provided with a map structure predefined by teachers. Moving through the study program, they can learn to understand these concepts and recognize the valuable examples of their work in the learning process. During this work students can provide definitions for the concepts by describing them from their own viewpoints.

Students use many different approaches when representing the same set of concepts. Based on a review of the students’ maps, the study [31] has identified several commonly occurring situations:

- added/missing elements – some students insert extra nodes between related concepts
- organizational variations – the same nodes are often represented by one student as a major concept connected to a set of subsidiary concepts (kids) while another connects the same concepts in a linear fashion; nodes are also frequently moved to different positions in a hierarchical tree
- cross-links – students frequently provide different cross-links between nodes of hierarchical map, hence reflecting personal differences related to integrative relations
- granularity and cardinality differences – a single node in one map may correctly match two or more nodes in the other one (a difference of cardinality)

Training is a key factor in producing a favourable outcome. Concept mapping without training is very problematic for students as they might not be able to structure and integrate the information in a proper way [4]. Because concept maps can be easy explained to learners, training and map construction can occur at the same time. It is not required to generate maps on the computer; they may be hand-written, as long as they are neat and easy to read. In several studies reviewed in [32], it has been proven that concept mapping can be introduced to the classroom with relative ease, from 50 minutes for high-school students to 90 minutes of concept map training for college students, which easily fits into nearly any schedule. Correspondingly, the time to grade maps ranged from 1 to 5 minutes, which appears not more time-consuming than multiple-choice quizzes or short essay exams.

Therefore, concept maps can represent any amount of knowledge. Their development helps students to see what they have acquired from the class. They also support students in making connections between class concepts and prior concepts. The maps reinforce knowledge integration by providing students with an activity that promotes such integration. As learning is a dynamic process, the personal concept map might never be complete [29]. It is constantly changing, as students deepen their understanding and potentially find more suitable evidence to underpin their development. Concept maps promote also discussion, particularly when the maps are placed onto the screen and students discuss them. Finally, the maps provide guidance on where students need additional instruction.

V. CONCEPT MAPS AS AN ASSESSMENT TOOL

A further strength of concept maps is their value beyond their role in assessment. Concept maps are considered to be a valuable tool of assessment procedures, as they provide an explicit and overt representation of learners’ knowledge through different informative, tutoring, and reflective feedbacks tailored to learners’ individual characteristics and needs [33].

Assessing what every student knows in a broad subject area is difficult. An important feature of concept maps is that they tend to be unique for each student. It is well known that human minds are highly different, especially, when it comes to interpretations such as, quality or completeness. It has been reported in [34] that different people would construct different concept maps, even if they answer the same question and share the same level of expertise. Such uniqueness prevents an instructor from doing a quick evaluation since the estimated object is not right or wrong, but rather more complex, elaborate, and precise in direct relation to the student’s understanding of the addressed domain. Therefore, the assessment process is prone to be complex, time-consuming and, in general, includes a strong degree of subjectivism, which should be mitigated [35]. The subjectivity appears when the teachers ask the concept maps they constructed for the same knowledge expressed in their lecture or textbooks.

To meet the challenge, the study [4] chooses to assess a student’s possibility to extract quantitative and qualitative information about the domain. In [34] partitioning of the evaluation process is proposed according to the steps followed for their creating, along with objective metrics that assign a score of each step. The maps are scored along several dimensions, including the comprehensiveness of the concepts, the volume of details in the map evaluated through the number of hierarchical levels, and the complexity of the links.

Application of concept maps as an assessment tool requires consideration of two issues:

- how the maps will be designed
- how they will be interpreted

Perspectives on addressing these two related issues have resulted in two methods each of which is usually accomplished by comparing the learner’s maps with the expert’s ones [18], [33]. At the former approach, known as a student-generated concepts approach, the maps represent the collection of concepts and connections a student identifies relative to an evaluated domain. Concept maps are constructed either directly by a learner or indirectly by an instructor based on the learner’s ideas. The strength of this approach is that emphasis is placed on the understanding how a particular student appreciates a specific domain. Individual differences as either concepts or links that are or are not included can be captured here. However, as the concept maps resulting from this method can be large, complicated, and difficult to interpret, it is usually problematic to provide a final judgment about a student’s knowledge. In the second method, called an externally-generated concepts approach,
the assessment represents a quantitative comparison between two concept maps – the student’s and the teacher’s map. Following this result, a map is interpreted by determining similarity between these two maps. The referent map might be constructed by a tutor based on his/her own knowledge or a map constructed to represent key knowledge in a textbook. The measure of similarity between the two maps states the grade of the student’s knowledge. In this approach, the labels of links can be ignored.

The maps submitted by the students are commonly quite diverse [18]. A couple of such examples from the authors’ practice are shown in Fig. 1. Some of learners resemble the maps created during the classroom activity. Such maps generally receive low scores on the comprehensiveness, level of detail, and complexity scoring dimensions. To receive a high grade, the map should show a large number of concepts, connections, and an extensive hierarchy among the concepts, showing that the student can differentiate between the levels in describing the elements of the domain. The large number of meaningful cross-links contributes to a high rating for link complexity because the cross-links appear primarily within clusters of concepts in the mid-levels and lower levels of the map.

The interpretation of the map can involve both quantitative scoring and qualitative judgments on the appropriateness of the teacher’s model. The assessment procedure involves scoring the student’s concept map along a variety of dimensions, such as the number of concepts, the number of links, the number of cross-links, the number of hierarchy levels, and the number of examples. These scoring data represent characteristic features of knowledge, such as breadth, depth, and connectedness. They stem from the theoretical motivations for concept maps including the analytical notions of categories, differentiation, and coordination. In addition to scoring along these dimensions, the maps can be inspected for the number of invalid propositions as well as the absence of critical concepts and links. To complete the grading, each of the dimensions is usually scored on a scale from zero to five.

For example, the distribution of scores assigned by [18] for concept comprehensiveness shows that most of the students receive high ratings. This suggests that by the end of the course, the students as a whole seem aware of the concepts that they had learned. The distribution of scores for the level of detail shows that more students receive the middle-level scores. This suggests differences in the students’ abilities to provide detailed description of concepts. Finally, the scoring distribution for link complexity shows the greatest variation. This shows that a key to distinguishing among the students who learned carefully and those who were less successful may be the ability to see complex connections between the different topics.

Clearly, concept maps are not a comprehensive assessment solution. They may require extensive time to interpret and may still remain ambiguous. Additionally, demonstrating through a concept map that students understand the relationships among the concepts does not guarantee that the student will be able to use the concepts to support design or other authentic engineering activities.

VI. CONCLUSION

Many teachers and students have difficulty in interpreting concept maps and in establishing relationships between the concepts and entities. Commonly, it is a rather complex and time-consuming task. Generating such knowledge models may require considerable effort to determine which concepts and relations can be included into the concept map and how they can be effectively processed. However, the proposed study shows that both the teachers and the students experienced in concept mapping produced better results in the course comprehension than those who were unable to construct the concept maps. Thanks to its dynamic and process-oriented nature, concept mapping enlarges humans’ opportunity to engage in the learning process.

ACKNOWLEDGMENT

This research work has been supported by European Social Fund (Project “Doctoral School of Energy and Geotechnology II”).

REFERENCES

