The Impact of Structural Characteristics of Concept Maps on Automatic Quality Measurement

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Abstract: Concept maps are often used in early phases of learning scenarios to externalise and possibly develop the conceptual understanding of a certain domain. An assessment of such maps can help to detect misconceptions and can serve as a basis for learner feedback. If used as a basis for agent-based scaffolding, the assessment needs to be calculated automatically by the system at run-time. Previous approaches have used an expert concept map as a reference for calculating such quality measures. This paper describes an approach that works without an explicit expert concept map but only uses more general domain ontology. To determine and adjust an automated quality measure student concept maps were collected and analysed by experts. The expert judgment was compared to certain structural measures based on graph-theoretical concepts and to enriched measures that additionally included ontology relations. It turned out that the inherent characteristic of concept maps as scale-free networks rules out certain structural measures as positive quality indicators.

Introduction

In a variety of pedagogical scenarios, the creation of concept maps is used to externalise and represent the conceptual or qualitative understanding of a domain. A typical activity can be the semi-formal visual encoding of important statements from a given text on the part of the students. The creation of a concept map from a text requires the reader to identify relevant concepts of the text and find appropriate relations between them. In this sense, they can, e.g., be used to develop and reify conceptualisations of scientific knowledge at an early stage of an inquiry learning process.

The context for the work presented in this paper is the European research project SCY ("Science Created by YOU", http://www.scy-net.eu/). The SCY project aims at engaging and supporting students in inquiry learning activities using computer tools such as simulations and modelling software. In SCY-Lab (the SCY learning environment), students work on missions with specific challenges. To flexibly meet the challenges of these missions, the configuration of SCY-Lab is adaptive to learners' capabilities and progress. In order to support the cyclic nature of inquiry learning, SCY-Lab provides tools and scaffolds, which provide just-in time support. Among others, SCY features concept mapping for working on texts and ontologies to enable intelligent agents to support domain-aware scaffolding.

A quality assessment of concept maps created by the students can provide valuable diagnostic information for teachers as well as for pedagogical agents and scaffolding mechanisms. Several suggestions have been made for automatically calculating such assessment measures, most of these using a reference concept map created by an expert on beforehand. In our approach, the student map is not compared to a predefined expert map but structural graph measures are used in combination with a "projection" of a given domain ontology. Such an ontology is part of every mission in SCY and provides semantic background knowledge for the pedagogical agents. The guiding question for our technical design and an ensuing empirical study was to check the possibilities of enabling the system to reliably interpret and analyse students' maps using an ontology and structural graph measures and to explore the ensuing potential of scaffolding.

Related Work

As concept maps can be used for multiple purposes in education, much related research can be found in several disciplines. Especially the use of concept maps for assessment purposes has been examined in several research studies (e.g. Stoddart et al., 2000; Rye & Rubba, 2002; Ruiz-Primo, 2004).

The "Reasonable Fallible Analyser" (RFA) by Conlon (2004) is similar to our approach in that it determines the quality of concept maps based on certain heuristic rules using structural and lexical properties. The score of a map is calculated by the comparison of the concepts of the learner's map with the concepts of a map that was created by an expert. To be able to deal with synonyms, the RFA is connected to a web-based lexical database ("WordNet") and a user dictionary that can be edited to define additional synonyms. Conlon claims (2004) that a quantitative score that represents an overall assessment of the concept map could help in giving the feedback to the learner. In contrast to our approach, the RFA utilizes (as many other concept map assessment approaches) a predefined "expert concept map" to compare it to the map produced by the learner.

Since, in the SCY project, a domain ontology has been created for each mission, we extract this "expert map" based on the ontology and the text that will be provided to the learners.

Betty's Brain (Gupta et al., 2005) is an example of an educational environment based on the "learning by teaching" paradigm. The learner teaches an avatar called "Betty" by designing a concept map in different topics. By switching to the query mode of the system, the learner can ask questions about the previously inserted concepts. A reasoning mechanism tries to answer these questions based on the concepts in the map. The focus of this work is not on developing a quality measure of the concept maps but on gathering information about the learner's knowledge in particular domains.

The COMPASS project (Gouli, Gogoulou & Grigoriadou, 2003) also deals with the usage of concept mapping in the process of learning. The central component of COMPASS is the learning environment, which allows the learners to work out several concept map based activities. COMPASS is independent of a specific learning domain. COMPASS aims at combining the learning process (using concept maps) and the assessment of the results. An automatic assessment is provided by comparing the students' solution with an expert map created by a teacher (Gouli et al., 2005) in a similar way as done by Conlon. Comparable to our approach, COMPASS makes use of ontologies to support the learner (and the teacher) during the learning process. Beside a domain ontology, which is used to generate semantic feedback, a student ontology and a "content knowledge ontology" are used to represent a learner model (level of domain knowledge, interaction data, etc.) and to store educational knowledge (Kilanioti et al., 2008).

Research Questions and Objectives

The initial leading goals for our research efforts were the creation and validation of a quality measure for concept maps and the testing of different scaffolds to be applied in the creation phase that might positively influence the map quality. To determine a quality measure, in addition to semantic matching also several graph-based measures were taken into consideration.

As a reference criterion for our quality measure we asked four experts to assess the collected student maps. Our study was guided by the following research questions:

1. Which of the automatically determined variables correlate to the quality assessment of the experts and thus can contribute to a "valid" quality measure?
2. Do concept maps that were created with ontology-based scaffolding differ in any of the measures to the concept maps that were created without help?

The quality assessment by the experts was based on guiding criteria inspired by Marra (2002). Among the four criteria suggested in this proposal, we decided to concentrate on the first two of which (*crit1*) covers the observed completeness or richness of the concept map as compared to the given text source, whereas (*crit2*) relates to the interconnectedness of the map. The other two original criteria focus on the descriptiveness and the adequacy of the links and were not used in this first order comparison. However, we tried to avoid this dimension of variation by restricting the link labels to a small given set of typical relations. This also ensured a better match with the ontology.

Implementation

Our implementation is based on the SCY system architecture, which provides a blackboard-based multi-agent framework with access to different user/system logs at the backend and the SCY-Lab frontend for user interaction. For our purposes, we have modified and extended the existing concept mapping tool SCYMapper.

SCYMapper

The SCYMapper is a simple and easy to use concept mapping tool, i.e. it allows for managing graph structures, creating labelled nodes and edges, both in different shapes and colours. Moreover, it is easily configurable for special needs, so that new shapes or colours can be inserted or the default ones can be deactivated. In our case, we configured the SCYMapper to have only one blue shape and one simple edge, because our backend does not impose any semantics on the shape of a node.

One main advantage of the SCYMapper is that it is integrated in the SCY architecture. Technically, this means that all the actions that are done in SCYMapper are logged in a standardised format to the backend and that there are standardised message formats to easily send notifications to the SCYMapper.

Ontology

The knowledge that is used by the system to determine the progress and to calculate help proposals is encoded in an ontology that was created in the SCY project as a joint work of the educational and ontology experts. The core of this ontology was created in a traditional, manual way by using the Protégé ontology editor.

Additionally, a data mining process is used to semi-automatically add new keywords to the ontology. The advantage of such an ontology extension is that the system finds more concepts in a given text and, on the other hand, also recognises more concepts that students have created. This process uses the LDA algorithm

(Blei et al., 2003) to extract groups of keywords with a high probability of being related to ontology concepts from a given document repository. In most cases these resulting keyword clouds need manual renaming or regrouping, before they can be integrated with the ontology. In a next step, the ontology expert links these keyword clouds to the ontology in cooperation with the domain expert. This whole process is supported by a tool called Ontology Keyword Importer (OKI). Figure 1 shows the ontology on the left side, the keywords on the right side and the possibility to link keyword clouds to selected ontology nodes at the bottom. Links between ontology concepts and keyword clouds were created at such ontology nodes for which the domain expert saw a semantic connection.

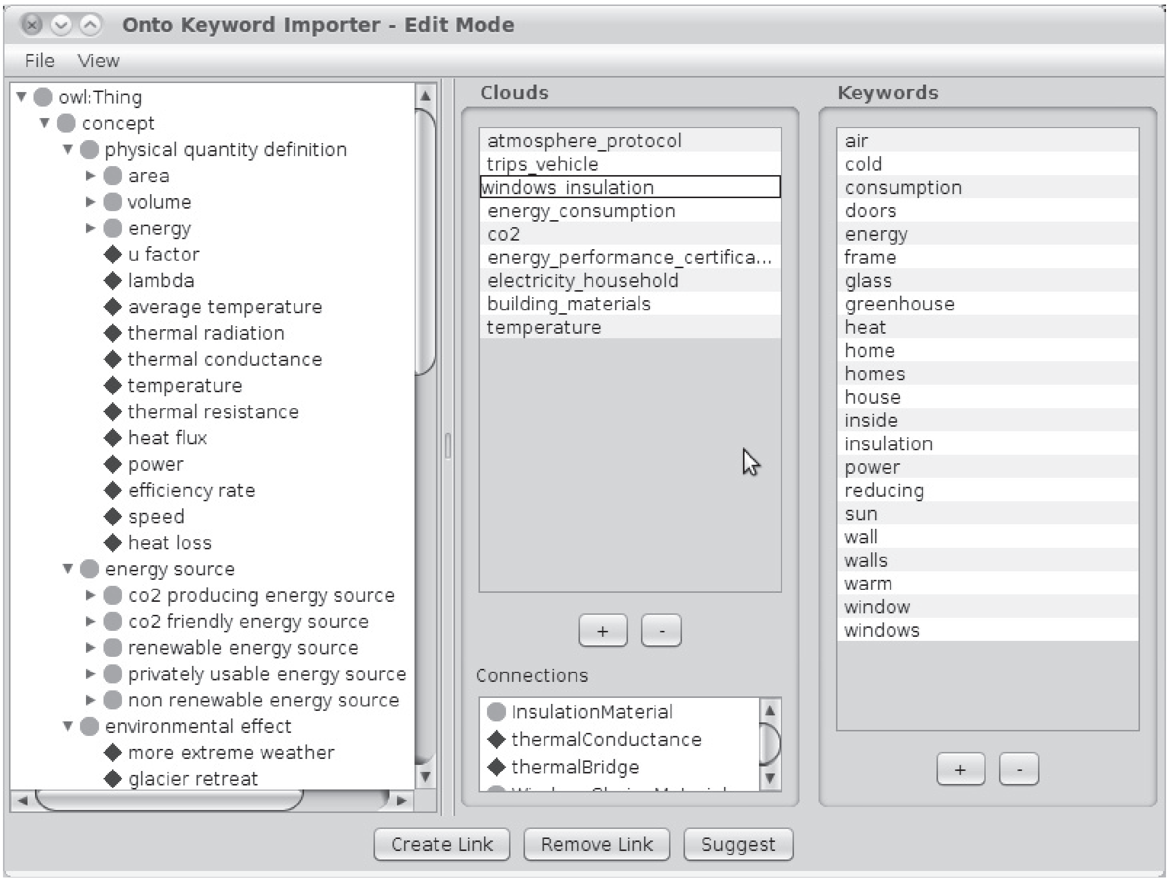

Figure 1. The interface of OKI (Ontology Keyword Importer).

Architecture and Agent Support

The part of the SCY architecture that is most relevant to this work is the pedagogical agent framework (Weinbrenner & al., 2010). It is based on a blackboard architecture (Erman et al., 1980), i.e. the different agents only communicate over a shared platform (the "blackboard") and not directly with each other. By monitoring and changing the contents of this platform, each agent contributes to solving a problem according to its specific competences. The SCY blackboard architecture is based on the TupleSpaces approach (Gelernter, 1985). In a TupleSpaces system, each participating system is a client of the central TupleSpaces server and is able to read, write and take tuples to and from the server. The concrete platform on which this is implemented is called *SQLSpaces* (Weinbrenner et al., 2007).

The SQLSpaces server hosts several subspaces that are used to store different kinds of data: The action space contains all actions in the common action log format. There is another space for all inter-agent communication, which is called the "command space". Finally, also the ontology is stored as a set of RDF tuples in the "ontology space". Four agents are working on these three spaces:

- The *enricher* is a so-called decision maker agent that only coordinates other agents. It recognises the need for help and triggers other agents. After having received the responses of the other agents, it writes a notification tuple in the command space.
- The *modeller* constantly monitors the user actions in order to inform other agents about the current state of the users' concept map.
- The *notifier* waits for notifications to be written in the command space and routes these to the user.

- The *proposer* responds to the enricher to return the next hint to a learner.

When the *proposer* is asked to generate concept or relation proposals, it first fetches the current user map from the *modeller*. Then, it determines the "ontology projection" by matching the given text against the concept in the domain ontology. This matching involves the following steps: First, all words in the text are stemmed and compared to the stemmed words in the ontology. Then all ontology terms that occur in the text are collected. Ensuingly, the same is done for the semi-automatically added keywords. Next, all the ontology concepts that have been found in that way are inter-linked by using the original ontology relations. This cut of the ontology is now compared to the user's concept map and all the missing concepts and relations are determined. In order to propose the most important concepts, for each concept of the ontology projection a relevance value is calculated that depends on the graph centrality (degree) of the concept. Ontology terms that appear literally in the text are considered more relevant than keywords that have a common stemmed form with one of the words in the text. So all the terms that have been found are ranked according to their aggregated relevance value and the top ranked terms (in our case the top 3) are presented to the user.

In spite of stemming and of the keyword cloud extension, still not all student terms can be matched to ontology terms even though there may be semantic equivalences. To solve this problem, students can explicitly declare a term used in a concept node of a map in SCYMapper as a synonym of a proposed concept (see "Concept already exists!" option in Figure 3). This will result in a message to the internal agents that will then establish an explicit synonym link and will handle this synonym accordingly.

Figure 2 shows this matching process in a visual interface that has been used for inspecting and demonstrating the system. On the top the text, used by both the students and the agent, is displayed. The areas highlighted in yellow contain the terms that have been matched according to above mentioned matching strategy. Below this, on the right side the state of the current student concept map can be seen. On the left side the ontology projection that corresponds to the text is located. Here, the green labels mark those concepts of the student's concept map that were found in the ontology, whereas the red labels identify the most relevant but missing concepts, which are to be proposed to the student as scaffolds.

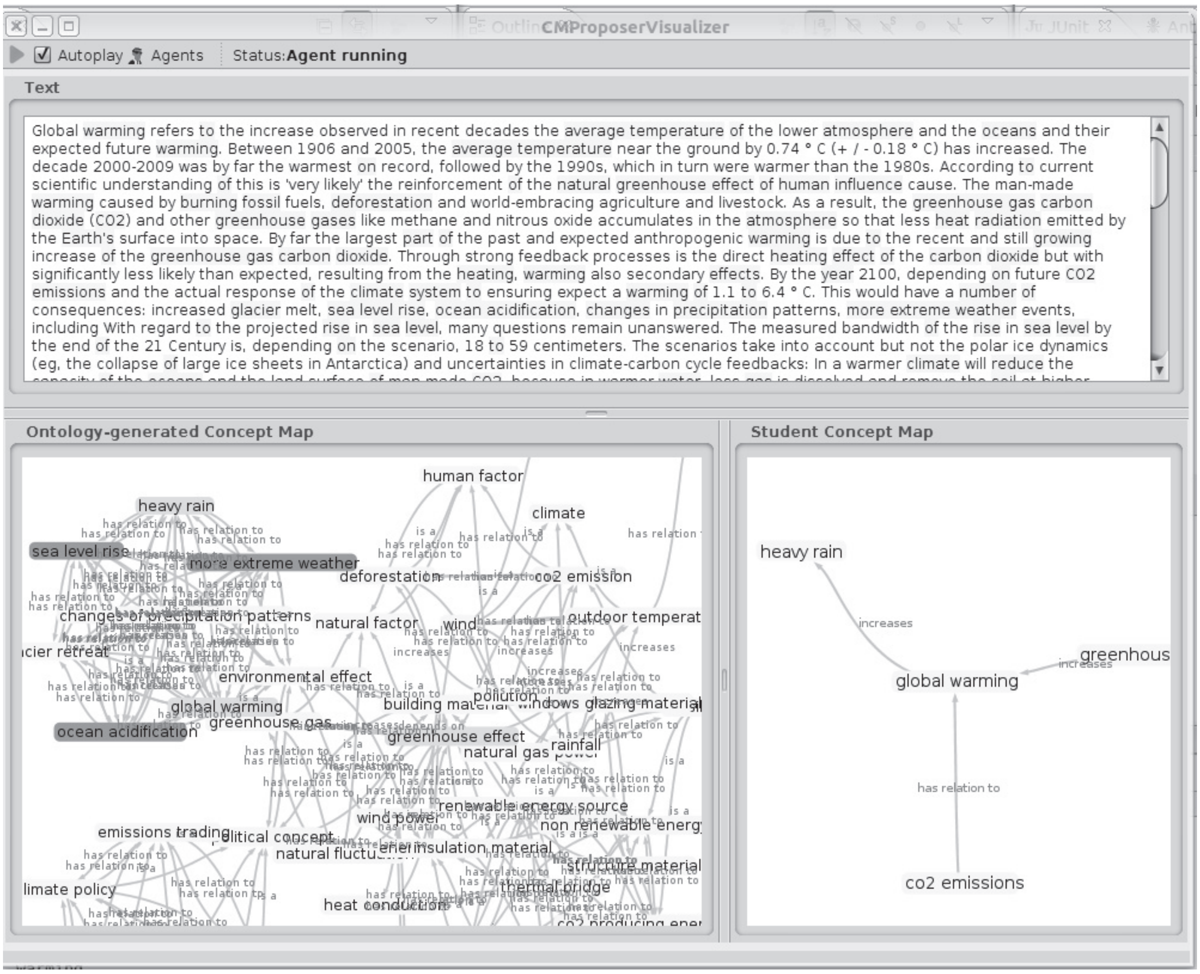

Figure 2. Visualisation of the proposer agent

Study

Building Blocks for Quality Measurement

One main goal of our study was to find an adequate, automatically computable (possibly multi-factor) quality measure that would be maximally consistent with human expert judgement in terms of a high correlation to expert evaluation scores for *crit1* and *crit2* (see section 3). One type of factors or variables were based on the graph structure, such as the number of nodes ($\#N$) and edges ($\#E$), the relation/concept ratio (RC) and the density (D, calculated by $(2\#E / \#N(\#N-1)$). On the other hand, the ontology was used to calculate the number of nodes ($\#N_{\Omega}$) and edges ($\#E_{\Omega}$) in a map matched by the ontology. The matching process involves stemming of the terms, removing stopwords and ordering them alphabetically in order to cover different formulations of the same concept, for instance the concept “increase of sea level” would be processed to “increas of sea level”, then “increas sea level” and finally “increas level sea”. The ordering is particularly important in order to handle the concept “increase of sea level” in the same way as the concept “sea level increase”. Finally, also the weighted number of such concepts ($\#N_W$) was taken into consideration. The weighting calculated as the graph theoretical measure of degree centrality for each node of the ontology projection.

Study Design

Thirty-seven pupils of a secondary school in Duisburg, Germany, aged between 16-18 years participated in the study. Participants were introduced to concept mapping and the usage of the SCYMapper, including a demo, in a 45 minutes introduction. After the introduction, everyone received two pages of text about the global warming and a highlighter pen. Every pupil worked individually first highlighting the relevant keywords in the text, and afterwards on one computer. They were divided into two groups of twelve and one group of thirteen pupils. The three groups worked on different versions of SCYMapper offering different types of help. The on-demand group had two additional buttons, which were labelled "Request concept help" and "Request relation help". The second group received automatic help after an exploration phase of three minutes and a minimum count of five concepts. The last group did not receive any help. The help for the first two groups appeared in the right part of the SCYMapper screen (compare Figure 3).

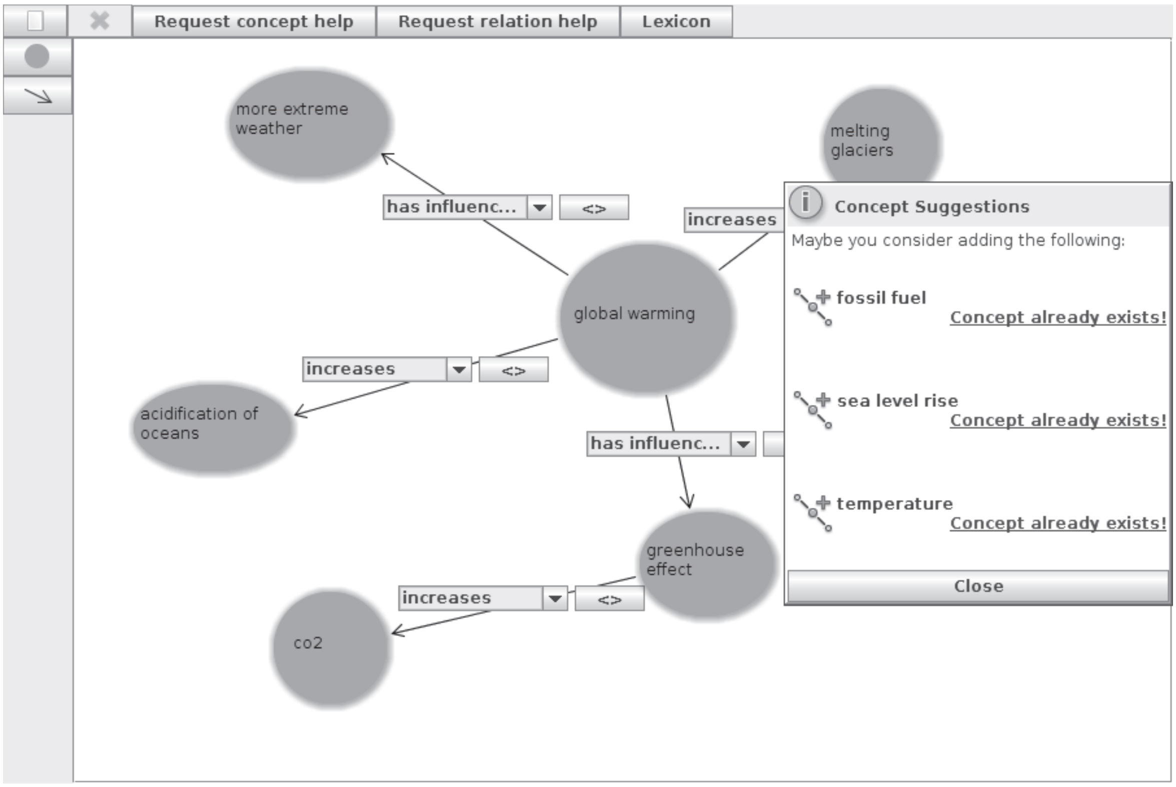

Figure 3. Screenshot of SCYMapper with automatic help.

The group without help worked in a different location to really prevent them from accessing help information. The other two groups worked together in one room. The task was to create a concept map from the given text using the SCYMapper tool. The three suggestions displayed in the example situation of Figure 3 were generated using the approach described above, i.e. considering not only their occurrence in the ontology projection but also their degree centrality as a measure of relevance. The option "Concept already exists!" should be selected by the students to express that they had already covered this concept by another term (not in the ontology). In a next step, they would be asked to identify this term in their map. Then this term would be marked as a synonym of the suggested one.

Pupils were assigned to groups based on a questionnaire that covered prior experience with concept mapping techniques as well as knowledge and interests in the domain of global warming and environmental issues. The results were mapped to a numerical scale, so that the pupils were assigned in a balanced way to the three groups. The text given to the pupils dealt with global warming. It consisted of 942 words and started with a definition of the phenomenon of global warming followed by a short explanation of the assumed causes. The main part of the text enumerated detailed consequences and effects on the ecosystem and the human living conditions. Finally, possible technological and geopolitical countermeasures were mentioned.

Thirty-seven concept maps and the corresponding action log sequences were collected and analysed. Additionally, the pupils' concept maps were assessed blindly by four experts on a scale from 0 to 4 based on the guiding criteria. These results were also evaluated according to the group division.

Results

For both criteria (completeness and interconnectedness) that were used to judge and to measure the quality of the students' concept maps, correlations were calculated using Pearson's product correlation. As for research question 1, the correlations between the automatically calculated values and the experts judgements were calculated. The human assessed completeness correlates positively with the number of nodes $\#N$ (r=.792, p=.000), the number of edges $\#E$ (r=.741, p=.000) and the weighted nodes $\#N_W$ (r=.387, p=.018), whereas the interconnectedness correlates with the number of edges $\#E$ (r=.625, p=.000) and the relation-concept ratio RC (r=.680, p=.000; all Pearson correlation). In sum, results showed that there is a medium to high correlation between the human judgement and the automatic assessment.

Table 1: Correlations of structural measures with expert judgments

	Criterion 1 (completeness)	Criterion 2 (interconnectedness)
# Nodes (#N)	r = 0.79, p = 0.000	-
# Edges (#E)	r = 0.74, p = 0.000	r = 0.63, p = 0.000
Density	**r = -0.53, p = 0.001**	r = -0.26, p = 0.11

As for the structural measures, we found that the graph-theoretic density D was not a good quality predictor, but in contrast negatively correlated especially with the expert judgment on criterion 1. Very likely this is due to the nature of network/map evolution: The density of a map tends to decrease with growing number of nodes, whereas the RC coefficient tends to be stable. Thus a higher density indicates a smaller map and, accordingly, correlates negatively with *crit1* (r= -.528, p=.001). This phenomenon corresponds to the evolution of so-called scale-free networks (Barabási & Bonabeau, 2003) based on a mechanism called "preferential attachment", expressing the tendency to attach new nodes to those already strongly connected. As an unexpected side-effect, yet retrospectively not surprising, our study corroborates that concept maps evolve in a similar way. It is indeed of high practical relevance that, as a consequence, graph-theoretic density of concept maps is inappropriate as a quality predictor. Instead, the ratio between number of links and number of concepts (#E/#N) can be used as an indicator of interconnectedness (r= .2, p=0.2 for *crit1*, r=.68, p=.000 for *crit2*).

Due to unrecognised semantic equivalences between the terms used by students and ontology concepts, the values for $\#N_\Omega$ and $\#E_\Omega$ were not very high as compared to $\#N$ and $\#E$. The main reason for that was the rare usage of the explicit synonym declaration ("Concept already exists!"). Therefore, the corresponding ontology-based variables also did not show a significant correlation to the expert judgments. However, we still decided to integrate them as a semantic correction into our formula for *qm* for two reasons: First, the structural values ($\#N$, $\#E$, etc.) lack a connection to the content so that a concept map with only dummy concepts would always score higher the bigger it gets, irrespective of node content. The second advantage is that the semantically weighted measure provides an estimation of expected values like size or relation-concept ratio. Without this a concept map for a long (concept-rich) text would not be handled differently to a concept map to a short text.

To model the overall judgement, the different automatically assessed variables were composed additively after division by the corresponding value from the ontology projection ($\#N_\Omega$, $\#E_\Omega$, etc.). The resulting formula for the quality measurement *qm* is the following:

$$qm = \frac{1}{3}\frac{\#N}{\#N_\Omega} + \frac{5}{6}\frac{\#E}{\#E_\Omega} + \frac{1}{2}\frac{RC}{RC_\Omega} + \frac{1}{3}\frac{\#N_w}{\#N_{w,\Omega}}$$

The coefficients of the four quotients originate from the fact that *#N*, *#E* and $\#N_W$ contribute to one third to the completeness and *#E* and *RC* to one half to the interconnectedness aspect. This composite quality measure strongly correlates to the overall expert assessment *(crit1 + crit2)* with r=.776, p=.000.

Concerning research question 2, we wanted to investigate whether continuous help leads to a higher degree of interconnectedness. There is a positive indication for this from the *RC* value (1.17) as well as the crit2 assessment value (2.54), which is higher than the average (1.04, respectively 2.07). Probably due to the low sample size (N=37), this difference does not reach statistical significance. However, in informal discussions after the study the pupils reported a perceived benefit from the continuous help. Therefore, a continuation of the study in a larger scale is planned in order to confirm this.

Discussion

This study was originally conceived as a test of different versions of automated map assessment and different types of scaffolding support. Neither the benefit of enriching structural measures with ontology features nor the effects of automatic help and scaffolding could be clearly demonstrated. Yet, we have a found a clear indication of the scale-free nature of the student-created concepts maps. Scale-free networks as described by Barabási & Bonabeau (2003) have certain characteristics that influence the adequacy of graph measures for quality assessment. A scale-free network has a small number of highly connected nodes ("hubs") that, according to *preferential attachment*, are more likely to receive links from newly created nodes than others. Yet, the average degree in a growing scale-free network tends to be stable, which in turn implies that the density of the network will decrease as it grows (since *density = avg.degree / (N-1)* with *N* being the number of nodes). Figure 4 illustrates another typical feature of scale-free networks in our data: the *inverse power law* dependency of the number of nodes with a certain degree (degree distribution), for which a linear relation in the log-log graph can serve as a litmus test.

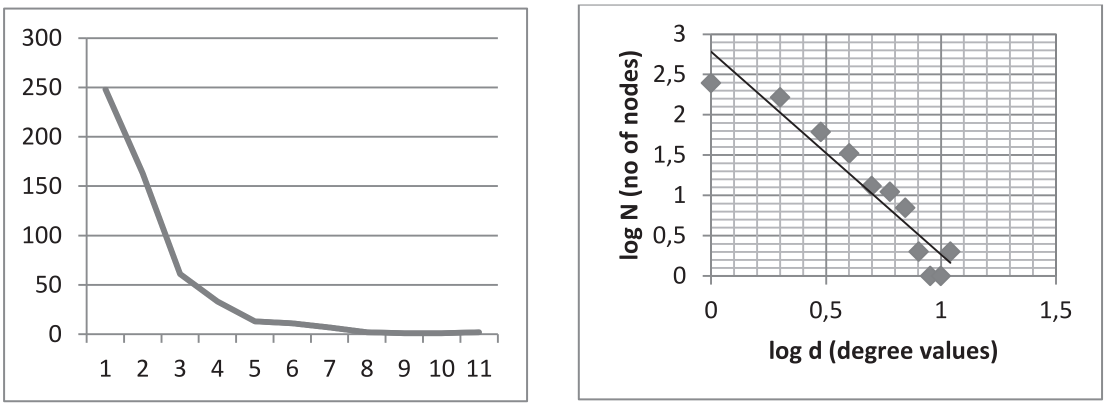

Figure 4. Aggregated degree distribution (from 37 maps) – left: number of nodes per degree value, right: log-log graph

In a panel contribution at ICLS 2010, Jacobson and Kapur (2010) have discussed the consequences of viewing ontologies as scale-free networks on modelling and understanding conceptual change. Their argument was a theoretical one, based on the assumption of ontologies (and also the personal conceptual models of learners) being of scale-free nature. Scale-free networks, although quantitatively dominated by nodes with lowest degrees, show a higher-than-random frequency of so-called *hubs*, i.e. very highly connected nodes. These hubs play a central role in the evolution of the model since they are the preferred points to which new nodes connect by "preferential attachment". We can further hypothesize that preferential attachment will dominate the "normal" development of a conceptual model. Newly arising hubs will indicate hot spots of conceptual change. If ever we should see hubs "collapsing" (i.e. dramatically loosing connectivity) this would indicate an abnormal situation, i.e., a kind of revolutionary change or paradigm shift in conceptual understanding. Concept maps created by students can be seen as indicators for such processes.

Ifenthaler, Masduki and Seel (2011) have used and compared a number of general graph theoretic measures to identify changes in cognitive structures, also relying on concept maps as external representations. Concept maps were collected at five different stages of a learning process. One of their findings was that the average degree of nodes tended to be constant over time (at a value close to 2). Yet, they did not trace this fact back to the scale-free nature of concept maps, but rather took it as an indicator of a de-centralised evolution of maps (p. 53). The model of *hubs* and *preferential attachment*, however, gives rise to more specific hypotheses about network growth.

General graph-theoretical measures provide a well-developed, yet still to be fully exploited inventory to analyse and model processes of conceptual development. Notwithstanding the lack of significance in the reported experiment, we still believe that a combination of such structural measures and semantic relations derived from an ontology is a key to a better understanding of learners' conceptual models. As an example of a structural measure, we had used the centrality of a concept in the ontology as criterion to prefer this concept in scaffolding hints (in case this had not yet been used by the student). Also, high values of betweenness centrality could, e.g., be used as indicators for "bridge concepts" that inter-link different areas or sub-domains of a conceptual model. Missing bridge concepts could thus indicate a need for better knowledge integration. Overall, we are convinced that there is still much to gain from applying general methods of network analysis to conceptual models externalised by learners in the form of concept maps.

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