Title:
Innovation in MCAD Education toward Competency Development using Negative Knowledge: From Theoretical Framework to Practical Implementation

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Introduction:
Nowadays mechanical computer-aided design (MCAD) systems are utilized extensively and on a broad base in the domain of industrial engineering. Those MCAD systems are used to create geometric models and virtual prototypes in order to support designers during decision-making activities, while also being used for product documentation purposes. The spread of MCAD systems within the mechanical engineering industry has increased in parallel with their technological development. The more these systems are able to provide new functionality, the more they are used to support product development processes. Similarly, with a considerable increase in their market share, systems developers are increasingly becoming aware of customer needs and are willing to improve the systems accordingly.

These days MCAD systems are complex systems which rely on geometric modeling kernels that are based on a fully developed technology, on top of which sophisticated modeling functions have been implemented in order to support different directions of geometric modeling, such as parametric/variational modeling, solid-surface integrated modeling, mesh modeling, and hybrid modeling. Individual aspects, specific to each modeling direction, are managed within these systems by means of different modeling approaches such as feature-based or direct/explicit solid modeling, surface modeling based on NURBS or sub-division surfaces, and mesh reconstruction from clouds of points. From an operative point of view, it remains rather difficult to determine which modeling approach is superior in respect to meeting the most requirements in practice, because the advantages and shortcomings of each modeling approach vary in nature, impact, and significance when being related to a specific application field or to a particular task in the product development process. For this reason, in order to meet the needs of customers, most modern MCAD systems are designed to integrate multiple modeling approaches. Usually this is translated directly into the definition of the system architecture and modeling functions, enabling support for both multiple model representations in a homogenous and coherent way and model interoperability. Those developments have led to considerable complexity in the models to be managed by modern MCAD systems, and an increase in requirements related to keeping models consistent and usable throughout all the different phases of the modeling process. This in turn puts higher demands on know-how and competency on the user side. It is essential to adopt appropriate design and modeling strategies. These are becoming an indispensable prerequisite for the efficient and effective operation of modern MCAD systems, despite widespread efforts to develop user-friendly modeling environments, accompanied by an intensifying trend to keep most technical details hidden from the user.

This scenario poses a new challenge for both vocational training and higher education, as it requires the development of teaching methodologies that go beyond the mere introduction of the individual commands needed to operate the system, or the development of generic guidelines and best practices for modeling. These are not sufficient in content or structure to fully support the development of the skill and knowledge components that make up a considerable portion of the competency now demanded for actually using, as well as benefiting fully from, the modeling functionality of modern MCAD systems. Recent research by the authors has been addressing the issues outlined above from a more theoretical point of view within the design and development of a novel teaching approach which integrates negative knowledge as one crucial element, together with traditional teaching methods, to support competency development within hybrid geometric modeling for the wider application context of product design. Our first promising results, in the form of a framework structure, central concepts, and an outline of implementation, have been presented and discussed in [4,7]. The aim of the current paper is to critically report on the concrete implementation of the newly developed teaching method and present a first theoretical, as well as empirical, analysis of the results obtained. Implementation and assessment studies have been conducted within an actual MCAD course, which is currently a part of the curriculum for the Laurea degree in mechanical engineering at the institution represented by the authors.

Scope and Objectives:

The newly developed teaching approach, which is now implemented in a current MCAD course, was specifically designed to improve the support of one of the major educational goals of the course, namely the development of modeling competencies, with particular reference to the development of strategic knowledge, in the field of hybrid geometric modeling. Within this context, hybrid geometric modeling is related to the development of integrated surface/solid geometric models aimed at supporting different types of design related issues, such as shape engineering, mold and cavities design for injection molding processes, and fixture design. Modern hybrid geometric modeling systems are a typical example of MCAD systems sharing multiple model representations, which, in the case of commercially available systems, usually consist of NURBS-based surface models and B-rep-based solid models. This type of modeling system provides the user with a large and rich set of modeling commands within a flexible modeling environment, and it even includes commands to assess the quality of the geometry of the models created. However, no support is provided from a strategic point of view; i.e. identifying the modeling strategy most appropriate in a given situation. Know-how on forming modeling sub-goals and effecting their efficient operationalization, in order to create “usable” models, is left solely to the user.

As the concept of a “usable” model is highly context-dependent, it can be approached from different dimensions and levels of abstraction. Within the work presented in this paper, three hierarchically structured levels related to product development processes have been identified, namely the geometric level, the analysis level, and the functional level. At the geometric level, a model is considered usable if it does not contain any severe geometric defects and spatial anomalies, which could impede the role of the model of being used in further steps of the modeling process. For example, the shape of a model is considered usable at the geometric level if its geometry is free of geometric deficiencies such as self-intersecting surfaces [7]. At the analysis level, a model is considered usable if it meets all the requirements necessary to perform a particular model analysis. For example, a model can be considered usable when its shape is sound and structured so as to allow for the conducting of a finite element mesh analysis or a computer-aided engineering analysis. At the functional level, a model is considered usable if it meets all the requirements for the manufacturability, assemblability, and functioning of an individual component or assembly that its geometric representation was designed for and implemented. For example, the shape of a model is considered usable at the functional level if it allows for injection molding production. For any model to be considered usable at a particular level, a necessary pre-condition is that it is considered usable at the geometric level. Due to the fact that the MCAD course, at present, is provided mostly to students who are novices in both geometric modeling and engineering, issues of model usability are currently approached from within spatial composition and shape, namely at the geometric level. However, in defining model deficiencies that are properly related to another specific application context, the framework can be expanded in a straightforward manner to include the analysis and functional levels.

Background and Approach:
Engineering expertise consists of acquired skills and knowledge in a specific domain (cf. [3]). In general, experts, in contrast to novices, exhibit a tendency to organize their knowledge within a holistic framework allowing for a fast perception of the significance of situations and possible consequences of actions. With increased expertise in a domain, cognitive processes become more and more responsive to situational cues, rather than being determined by abstract rules (see also [1,9,10]). Performing efficiently while committing almost no serious mistakes, i.e. knowing how to avoid grave errors and approaches which are inefficient in certain situations, is an essential feature of professional engineering expertise. This knowing what not to do in certain situations is attributed to knowledge referred to as *negative knowledge.*

Studies on the theoretical foundations and concepts of negative knowledge can be traced back to work in different fields. In artificial intelligence, Minsky [5] argues, in his work on negative expertise, that a great deal of what experts know about how to achieve goals and how to avoid disasters lies in knowing about what can go wrong in their domain and which actions might cause trouble and are thus better avoided. In education, the work of Oser et al. [6] on the practice of error culture uses a contrastive approach to define negative knowledge as a type of knowledge that relates to information on false facts and inappropriate action strategies. This approach can be seen as pointing towards negative knowledge as a form of meta-knowledge revealing a regulative impact on positive knowledge. In knowledge management, the work of Parviainen and Eriksson [8] focused on the declarative aspect of negative knowledge, the *knowing what not to know*, which is in contrast to the by nature more procedural aspect of *knowing what (not) to do*. More details on the declarative and procedural aspects of negative knowledge can be found in recent work by Gartmeier et al. [2]. This work discusses relationships with meta-cognition, and the epistemic potential to enable new insights into various knowledge-related and learning-related fields.

Individual stages within the development of a novel teaching approach, which systematically employs negative knowledge within a current newly designed MCAD course, have been approached by addressing framework development, concept mapping, implementation, and evaluation as follows. The basic design approach for the framework for negative knowledge was to aim for more similarity, which means reducing variety. This objective was achieved by formulating negative knowledge as an element of strategic knowledge, constraining actions within critical situations that would otherwise lead to errors and mistakes. Hence, it restricts actions that induce situations best avoided.

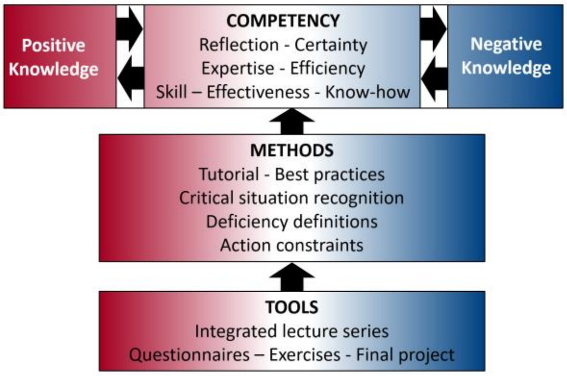

Fig. 1: Overview of methods and tools related to competency development for product design within the newly devised MCAD course.

Within the context as outlined earlier, this translates into the goal of supporting the development of know-how and skills aimed at providing for the creation of geometrically usable CAD models containing fewer undesirable structural elements. This can be achieved by systematically reducing model shortcomings introduced by errors and mistakes usually committed by novices, but never by domain experts. To define what constitutes an error or mistake to be avoided in respect to a particular situation and the quality of a CAD model, some elements of the concept of negative knowledge have been mapped to the concept of geometric entity deficiency. This concept is used as a qualitative measure to help express certain characteristics of situations during modeling. These characteristics usually lead to models being poorly structured and are thus better avoided. The actual implementation of the framework, currently realized within a newly designed MCAD course, is based on methods and tools that are comprised of integrated elements pertaining to positive knowledge and negative knowledge as shown in Fig.1 and further explained in the next section. Theoretical and empirical analysis of the current implementation is aimed at shedding some light onto the nature and extent of the impact which the systematic use of negative knowledge has on competency development within the educational context considered. Of particular interest are the support given to improving certainty in how to proceed in a task, to increasing efficiency during performance, and to enhancing the depth and quality of reflection on actions and performance.

Implementation and Evaluation:

To implement the approach and integrate it into the current MCAD course, central concepts of the negative knowledge framework were compiled into elements which were incorporated as components of the lecture series, laboratory exercises, and questionnaires. The lecture series is implemented as a construct which features a tight coupling between the teaching of theoretical subject knowledge and practical modeling exercises that are individually designed for different learning aspects based on both positive and negative knowledge. Results of the exercises are collected and assessed, to identify shortcomings and errors which usually remain hidden from students due to their limited domain knowledge and expertise. Results are then used for feedback and reflective discussions on critical situations overlooked and errors committed. As the approach is scalable to adjust to the student body profile, which varies in each semester, individual knowledge and skill development cycles can be adjusted. Currently, individual cycles are designed for the duration of one week in regard to a course unit, and then repeated five times. Exercise work is conducted within an affordable modeling environment, but one which is functionally adequate for the MCAD course. It is comprised of two commercially available CAD systems in the mid range, namely *Solid Edge* from Siemens AG and *Rhinoceros 3D* from Robert McNeel & Associates. The structure of this modeling environment serves two main purposes. First, it takes into account aspects related to both NURBS-based surface modeling and the exchange of CAD models between different system platforms, as is commonly required in practice. Second, it provides a surface modeling tool that allows for a relaxed approach to modeling since the quality of the geometric model is controlled entirely by the user. This system characteristic is one key feature which, from the point of view of a tool and modeling environment, explicitly supports the implementation of learning by error and the development of negative expertise. A web site has been developed for the distribution and collection of exercise material and the implementation and administration of a set of computer-aided questionnaires. These have been designed as a course survey, a self-report, and a test on subject knowledge. This web site is contained within the e-learning platform of the institution's engineering faculty using *Moodle*, an open source learning management system (LMS). Online participation in the questionnaires by students is both anonymous and voluntary.

Empirical data collection and analysis have been conducted within a multi-method research study in order to examine different facets of multi-component phenomena and to further description of and insight into the relationship between the newly developed and implemented approach and its contribution to innovation in MCAD education. Assessment of performance and learning outcome was carried out based on observation records during laboratory exercises, analysis of archival data, and results of questionnaires. For the archival data analysis, an unobtrusive method with high ecological validity was used. CAD models stemming from exercise assignments and final examination projects were assessed using association with categorical variables linked to concepts of geometric entity deficiency as defined within the framework of negative knowledge. A set of two questionnaires was considered as a form of self-report. One was administered before and the other after the introduction of negative knowledge into the current MCAD course. These served both as a correlational study and as a survey. The study was aimed at self-assessment regarding elements of competency considered as psychological constructs, such as confidence and subjective rating of personal development of subject-related skills and knowledge. As a measurement instrument for analyzing variations in response that correlate with relevant outcome variables, unipolar ordered response rating scales were employed. The survey, which employed both single-choice and open-ended questions, was aimed at a better understanding of how components used for the teaching of positive knowledge and negative knowledge were perceived by students and how the data on student opinions relate to dimensions of negative expertise.

Conclusions:

In this paper the framework, structures, and methods developed and used for the actual implementation and evaluation of a novel approach aimed at facilitating competency development for product design within MCAD education have been outlined and discussed. From a pedagogical viewpoint, the novelty of the approach lies in the systematic integration of traditional teaching methods with an educational approach based on negative knowledge. This approach draws on the potential to advance into higher education some elements of engineering expertise which are mostly obtained through workplace learning related to experience from errors and mistakes.

Theoretical and empirical examination of data related to learning outcomes, performance, and self-assessment, which have been obtained from course work, laboratory exercises, final exam projects, and a series of questionnaires, showed promising results as follows. Students developed a better understanding of central concepts related to the geometric usability of CAD models. This development was accompanied by an increased capability to recognize critical modeling situations that would have led to errors, thus helping to avoid mistakes typically made by novices. Also, confidence in subject knowledge and strategy formation increased substantially. This observation was, among other issues, reflected in data from self-assessment and laboratory exercises which correlated with the evidence that the students had advanced in both positive and negative knowledge. Results and insight obtained are currently being used as constructive input to improve laboratory exercises and questionnaires for the next academic year, and to provide better support not only for learning outcomes, but also for further collection and analysis of empirical data.

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