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Innovation in MCAD education toward competency development using negative knowledge: From theoretical framework to practical implementation

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ABSTRACT
With the rising importance of CAD models for product development and the recent strong promotion of hybrid geometric modeling from within the industry, the focus of teaching methods in current CAD education, as practiced in most institutions of higher education, needs to be reconsidered. From a pedagogical point of view, this situation represents a challenge, as it requires new, innovative teaching methodologies which advance the development of competency going beyond basic domain knowledge and skills limited to operating a CAD system. In this paper, a new and innovative direction for CAD education is offered, which is based on the integration of traditional teaching methods with an educational approach using negative knowledge. Central aspects of framework development and concept translation are presented together with promising results obtained through a multi-method oriented empirical study of this newly developed and now fully implemented approach.

KEYWORDS
Negative expertise; learning from errors; reflection on performance and outcome; certainty in goal-oriented action; strategic efficiency; CAD model usability

1. 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.

Modern 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, 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 (cf. [1]). Recent research by the authors has addressed the

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issues outlined above from a more theoretical point of view. This involves the design and development of a novel teaching approach which is focused on the utilization of negative knowledge (knowing what not to do) as one crucial element to support competency development within geometric modeling for the wider application context of product design. First results, in the form of framework structure, central concepts, and an outline of implementation, have been presented and discussed in [19,27,28]. In the academic year 2015/2016, some promising results were achieved with a limited number of volunteer students. As a result, the proposed framework was fully implemented and provided to all students of the MCAD course, which is currently a part of the curriculum for the Laurea degree in mechanical engineering at the institution represented by the authors. The aim of the current paper is to critically report on the implementation details of the newly developed teaching method and present a first theoretical and empirical analysis of the results obtained. Note that in order to appreciate the results presented in this paper to the fullest extent, readers should be aware of and familiar with some definitions and concepts central to this research, such as geometric entity deficiency, critical modeling situation, and action constraint, which were introduced in the author's previously published work, but cannot be fully presented again here due to manuscript length limitations.

2. Scope, background, and related work

2.1. Background and related work

Recently, there has been a noticeable increase in interest in MCAD education. Amongst other reasons, this is due to the ever-increasing adoption of MCAD technology in industry [6]. Improvements in MCAD education are aimed at developing better competencies in respect to various issues identified in the literature. Most work is focused on the acquisition of strategic knowledge, which is related to the identification of suitable procedures aimed at creating valuable models [4]. This can be achieved by concentrating on the development of competencies aimed at producing models that have to be usable / re-usable in the product development process (cf. [2]). In respect to the development of competency regarding the design of usable / re-usable CAD models, it appears that the majority of work within the current literature addresses this topic from the viewpoint of feature-based solid modeling techniques. Here this aspect can further be sub-divided into two classes of problems, namely the development of easily alterable models that are required in the design phase, when a model needs to be adjusted to meet new design requirements, and the development of models for optimization purposes. In the case of the latter, the development of 'quality' models requires a proper geometrical / topological specification, suitable to allow further analysis or simulation to be performed on the model. The problem of model alterability is usually addressed as an issue related to design intent preservation (cf. [26,33]). Camba et al. and Salehi et al. [2,34] provide an extensive review of how these issues have been addressed regarding the use of so-called *feature-based* or *history-based MCAD systems*. In this context, the MCAD industry responded to the model alterability issue by promoting a new modeling paradigm, namely explicit modeling (see discussions in [20]). The CAD model quality can be addressed from different perspectives. In [18] a CAD model quality taxonomy is proposed, which is based on the types of errors that may affect the model. This taxonomy considers morphologic, syntactic and semantic errors, related to both polynomial mesh and B-rep (feature-based) models. Those error types are considered meaningful, because they can affect further required model related tasks, like model simplification, interoperability and model reuse. Looking at these problems from an educational perspective, error classification is a kind of metric to measure the failure of teaching strategies, as the learning outcomes of good teaching strategies should have prevented the introduction of such errors into the models in the first place. In certain situations, this requires that CAD users also have sufficient knowledge related to other sections of the product development process that should be taught within aspects of computer-aided product creation (cf. discussion in [5]).

Many studies on expertise investigate the cognitive structures and processes of experts to gain insight on what it is that experts know and, even more importantly, how they organize and employ this knowledge to achieve that extraordinary performance, which distinguishes experts from novices [9,10]. Engineering expertise consists of acquired skills and knowledge in a specific technology-related domain (cf. [15,40]). 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 (cf. [31]). 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 [3,23,41]). 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* (cf. [7,25,29]).

Research on the theoretical foundations, concepts, and application of negative knowledge can be traced back to studies in several different fields. In philosophical and social studies concerned with science and technology, negative knowledge is found in many instances to be related to work on the unknown within the subject of ignorance and uncertainty. In the literature two major types of ignorance are identified and referred to as *known unknowns* and *unknown unknowns* [11,42] and they are synonymous with what Smithson defines as *conscious ignorance* and *meta-ignorance* [36]. Both known unknowns and unknown unknowns derive from a lack of knowledge. Known unknowns usually denote knowledge of what is known about the limits of knowledge, encompassing things that we know that we do not know. In [16] negative knowledge is considered a type of meta-knowledge representing a special case of known unknowns referring to the limits of knowledge within science. Ignorance, as unknown unknowns, relates to a lack of knowledge, such that we are not aware of it. For example, it encompasses all the things we think we know but do not (errors). Early work on unknown unknowns can be found in [37]. As pointed out by Gross in [12], the revelation of such ignorance can be a source of surprise, because unknown unknowns are completely beyond anticipation. Note that within this line of studies tacit knowledge (cf. [30]) and all the things we do not know we do, is usually referred to as *unknown knowns* (cf. [42]). In artificial intelligence, Minsky [22] 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 and Spychinger [24] 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 the examples discussed in their work, the authors also stress the importance of practical experience within a concrete work context, as that is the primary method of obtaining negative knowledge (see also [17,25]). In knowledge management, the work of Parviainen and Eriksson [29] 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*. In their work they distinguished two types of not-knowing relating to the informed and uninformed methods of an individual lacking knowledge relevant to expertise. This distinction addresses in the former case an awareness by the individual of his lack of relevant knowledge, while the latter case supposes both a lack of relevant knowledge and a lack of awareness of this very fact (see also discussions in [13]). Recent related work in the field of management learning within studies on the lack of knowledge in the context of organizational ignorance and the management of the unknown can be found in [32]. Further details on the declarative and procedural aspects of negative knowledge can be found in recent work reported in [7,8]. This work discusses relationships with meta-cognition, and the epistemic potential to enable new insights into various knowledge-related and learning-related fields. It also considers 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.

2.2. Scope and objectives

In the field of MCAD education, most, if not all, of the approaches presented in the literature are based on the development of positive knowledge, that is tutorials that show how to employ the commands used to operate systems, best practices to drive the design intent, guidelines for creating appropriate models, etc. In general, all these approaches are focused on the development of competencies in *what* to do in normal, idealized situations, and *how* to do it. However, this approach has several shortcomings and limitations, as it does not provide any support for reducing mistakes or for handling of error situations, and it also lacks any structural and conceptual elements for making transparent the reasons *why* some procedures and strategies, as recommended in tutorials and best practices, are more efficient and effective than others. To overcome the current impediments, the authors have devised a novel educational framework, aimed at integrating the development of positive knowledge with the development of negative knowledge and doing this from both sides, namely teaching and learning [19, 27,28]. The design of the novel framework was motivated by, among other things, work on negative expertise and workplace related learning and error handling, with a particular emphasis on issues related to negative knowledge. This is of particular importance within the context of competency development as, according to current research (see again details in the previous subsection), it can contribute to fostering certainty about domain knowledge and related actions when solving a problem. It also directly influences performance by allowing for the identification and correction of inadequate methods of proceeding, and thus increasing the efficiency of problem solving, while additionally promoting the quality and depth of reflection on actions. After some promising outcomes, which were achieved with a limited number of volunteer students during an initial experimental implementation of the recently developed approach (for theory-related details on concepts and framework structure developed within this approach see [19,28]), the results of a careful analysis of both qualitative and quantitative data provided sufficient grounds to facilitate a full implementation. We have proceeded, therefore, with empirical research from within a current newly designed MCAD course, in which over 150 students are participating. As data collection continues and empirical analysis advances, the objectives of the current paper are to critically report on this educational research in progress, related to both the implementation and the empirical data analysis. The project is now moving from the initial experimental stage to a full-scale program conducted within the actual setting of higher education, as it is aimed at innovating current MCAD education and improving the competency of students to create 'usable' CAD models.

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 (denoted as levels 0, 1, and 2, as shown in Fig. 1). At the geometric level, a model is considered usable if it does not contain any severe geometric and topological defects, or spatial anomalies, which could impede the role of the CAD model for 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 both geometric deficiencies such as self-intersecting surfaces (cf. [28]) and topological deficiencies such as loss of connectivity. 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 (FEM) analysis or a computer-aided engineering (CAE) analysis. These

Usability Level	Deficiency	Expected failure
2	Functional constraints Production constraints	Functioning Production
1	Small entities Detailed features	Meshing Computation time
0	Topological errors Geometrical errors	Modeling operation Model exchange

Figure 1. Deficiencies and failures related to different usability levels.

analyses both require, amongst other necessities, that the CAD model be free of small entities and irrelevant features (see also [38]). 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 that was designed for manufacturing by injection molding is considered usable if rounds and thickness parameters are defined within adequate value ranges and draft angles are present (see also [21]). 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 of abstraction. 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.

3. Approach and theoretical framework

3.1. Basic design approach

Within the current newly designed MCAD course employing a novel teaching approach which systematically utilizes negative knowledge, the development of individual stages has 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. Thus we are restricting actions that induce situations best avoided.

Within the context 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 usually committed by novices, but never by domain experts. To define what constitutes an error to be avoided in respect to a particular situation and the quality of a CAD model, some elements 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

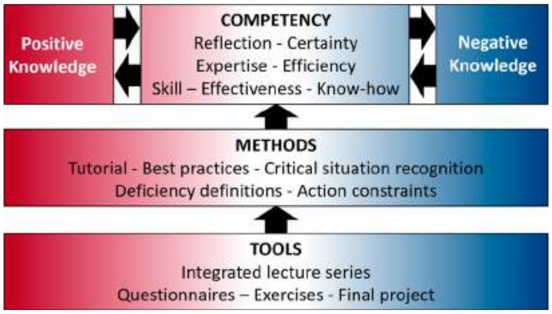

Figure 2. Overview of methods and tools related to competency development for product design within the newly devised MCAD course.

within the 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. 2 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 being considered. Of particular interest is 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.

3.2. Concept of negative knowledge

Considering negative knowledge as 'knowing what not to do' may initially seem, from a theoretical point of view, to further a conceptual approach which includes an almost boundless set of possible actions that must not be done. However, from a more practical point of view, our interest is limited to those actions that can have a negative impact on particular tasks within a given frame of reference. From this viewpoint, within our field of interest, the aim of the negative knowledge framework is to restrict the actions that induce situations best avoided (critical situations) in the context of MCAD modeling. This can be achieved by conceptualizing negative knowledge, from a theoretical point of view, through relationships to desirable situations, which in turn indicate what is considered a good model (configuration) within a given context employing normative knowledge. Here, desirable situations represent a reduced set of all possible situations (desirable / undesirable). In this scenario the nature of similarity of desirable situations is determined by reducing variety (cf. [19,27]), which in turn is realized by avoiding undesirable situations by means of restricting actions that have a high tendency (according to what we know and believe to be true) to lead to them. Hence, negative knowledge in terms of knowing what not to do in a certain situation can be conceptualized as a form of action constraint. It limits the variety of situations, and consequently their number, by preventing actions that might result in constellations (model configurations) considered not good, i.e. situations deemed undesirable. This concept now features both a quantitative and a qualitative method of determining similarity as an overall defining structural property of situations, which are considered desirable.

3.3. Concept of critical situation and action constraint

A situation can be abstracted as a set of relations associated with particular sets of model configurations, possible actions, and individual goals and sub-goals. This concept of a situation is, in turn, defined by the model and the context (cf. [19,28]). For instance, a concrete situation is determined by the actual model configuration in a given context with a specific goal. Within our framework, and in consideration of the goal of creating a 'usable' CAD model, an actual situation can now be determined by the MCAD system, the user, and the geometric model. Within this scenario, a so-called *critical situation* represents a situation where a model configuration can be changed into a deteriorated and downgraded model configuration, by means of performing actions deemed inappropriate, among all actions possible. For example, a MCAD system user can introduce a defect into the geometric model by means of executing a particular modeling command provided by the system. Properties that define the quality of the configuration, and whether a model is degraded, are related to the normative knowledge of the application domain.

Configurations that describe a model configuration in a certain context which is significant in respect to action constraints, which in turn are associated with individual actions, are so-called *significant model configurations*. Within the framework, significant model configurations relate to situations determined by actions considered relevant in respect to a user task goal, like geometric modeling actions. These significant model configurations can be related through a mapping to concrete constraints, limiting the actions possible in a particular situation. Here those concrete constraints are denoted as *action constraints,* and are formed into a concept which provides a means of taking into account the portion of negative knowledge, mostly tacit in nature, which relates to action constraints spanning various different types of situations. Within our framework, action constraints are used to specify which commands or sequences of commands should not be applied in a significant situation. Within the framework, actions that remedy the consequences of errors, and thus reduce model deficiency, are regarded as a form of recovery. Note that, unfortunately, the concept of action as a goal-oriented behavior, as established and successfully used in action theories within industrial and organizational psychology, cannot be used in its explicit form in the framework presented. This is due to the non-behavioral and highly reflective, as well as anticipatory, character of negative knowledge.

3.4. Concept of geometric entity deficiency

The concept of geometric entity deficiency 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 best avoided. This concept can be seen as one important element supporting definition and evaluation of what is to be avoided in respect to particular situations and contexts.

Deficiency represents the loss of one or several characteristics of a geometric entity meaningful in a certain application domain. Not only are those characteristics an important defining property of individual entities at a common level or dimension, but they may also become a significant element as an input for the definition of a higher dimensional entity. Geometric entity deficiencies are sub-divided into those for single entities and those for compound entities, with the former relating to curves, patches, and solids, while the latter relate to polycurves and polysurfaces. Details and definitions of individual geometric entity deficiencies and all geometric entity types, as related to the context of hybrid geometric modeling can be found in [27,28].

4. Implementation and evaluation

4.1. Outline

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 the students' 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. The collection and analysis of empirical data have been conducted within a multi-method research study (cf. [35]), currently consisting of four parts. Each part is dedicated to the assessment of performance and learning outcomes in regard to competency development, using a different study design and outcome measure. Surveys on self-rated competency and opinions on teaching methods used in the newly designed course were also administered to support evaluation.

4.2. Framework translation and integrated course structure

A structural overview of the main tasks is given in Fig. 3. This shows how the concepts of negative knowledge and geometric entity deficiency, as introduced and developed, are used to implement the approach and integrate it into the current course work for MCAD education.

The process, as represented in the overview in Fig. 3, starts out with a traditional teaching task, typically in the form of lectures provided by the teacher. These lectures are aimed at introducing elementary subject knowledge related to basic concepts and system functionality. At the end of this part of the course, the students have acquired knowledge about modeling guidelines (positive knowledge) in form of successful modeling examples, a list of best practices, modeling command descriptions, etc.

To make explicit to the students the drawbacks that can derive from a poor modeling strategy, in the next step of the process the students are asked to use models that they have previously created, as those models will surely contain deficiencies that will prevent or impede their use. During exercises within this model use task the students will directly experience how the deficiencies present in their models will impact or even prevent their efficient use.

In the last step of the process, models developed by the students and failure situations that emerged, are collected together and critically analyzed by the teacher. During this phase, the teacher will explicitly relate failure situations to model deficiencies and inobservance of best practices, while also discussing critical modeling situations and related actions that should be avoided. Next, analysis results from all the information collected and discussed are organized and translated into so-called *situation boxes*, which are aimed at explicitly representing the negative knowledge captured during the analysis process.

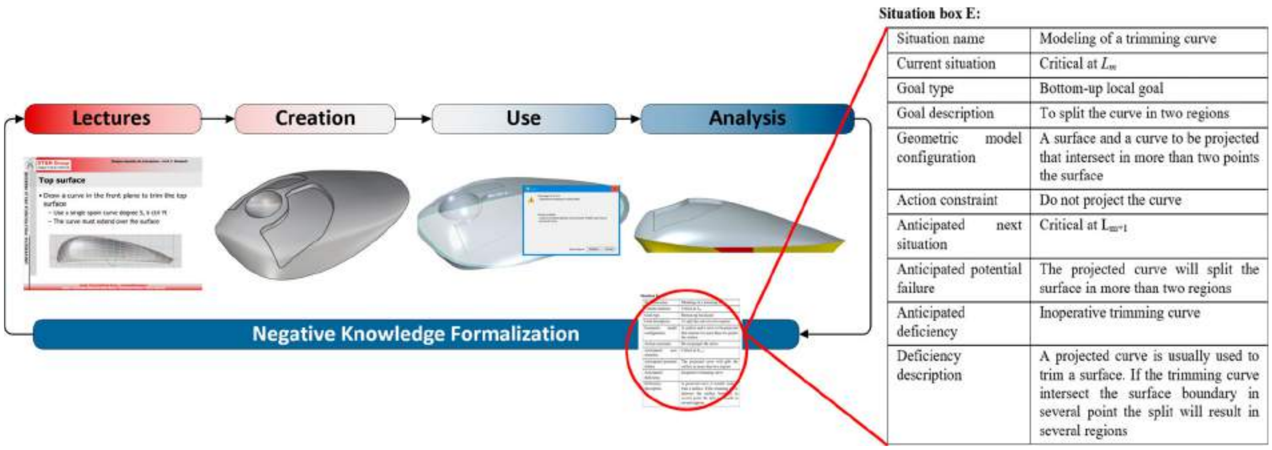

Figure 3. Competency development within the newly developed MCAD course structure.

More details and examples of situation boxes as shown in Fig. 3 are reported in [28]. The negative knowledge developed during this step will improve not only the students' technical competency, but also their capability in self-reflection and their certainty about modeling strategies aimed at preserving the model quality. It should be noted that the proposed approach can be accommodated for different educational contexts and that it can be applied on a scalable basis. For example, customizations can be put in place at the course design level, where the model use exercises are devised on the basis of the students' learning levels and the expected teaching results. The approach is also scalable in the sense that the teaching / learning process can be iterated as many times as required in order to cover all individual elements of the course such as surface quality, geometric soundness, and model alterability. Within the individual steps of each iteration, the students will benefit from both the positive and the negative knowledge developed during the previous cycle. Moreover, the proposed approach can be tailored toward different degrees of competency by adjusting the criteria for the assessment of model usability associated with different levels, that is usability at the geometric level, the analysis level, or the functional level.

Implementation of the approach as outlined earlier and integrating it into the current MCAD course, requires – among many other things – the set up of an affordable and functionally adequate computer-aided modeling environment for the MCAD course. Therefore, two commercially available CAD systems in the mid range, namely *Solid Edge* from Siemens AG and *Rhinoceros 3D* from Robert McNeel & Associates, were deployed. 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. Hence, any kind of surface can be generated, including self-intersecting surfaces and surfaces of poor geometric quality. Note that this system characteristic is one key feature which, from a tool and modeling environment point of view, explicitly supports the implementation of learning by error and development of negative expertise as discussed elsewhere in this paper. In order to manage the interaction between faculty and students, including the administration of procedures and deadlines for the distribution and collection of exercise material, a web site for the course has been developed within the e-learning platform of the institution's engineering faculty using *Moodle*, an open source learning management system (LMS). Note that the LMS is not used to create any domain subject related contents (see also discussions in [39]). This LMS is also employed to implement and administer a series of computer-aided questionnaires, which comprise an intermediate survey and a final survey. These surveys represent a central part of the multi-method research study, which is described in detail in the next sub-section.

4.3. Collection and evaluation of empirical data

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 outcomes was carried out based on observation records during laboratory exercises, analysis of archival data, and results of questionnaires. For the archival data analysis, which is an unobtrusive method with high ecological validity, 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 the 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. The four individual parts of the multi-method study pertaining to the different facets of multi-component phenomena, as briefly outlined above, are now described in the next sub-sections.

4.3.1. Part I: Assessment of learning outcomes based on questionnaires

Aim and study design. This part of the multi-method study is aimed at determining aspects of competency development by examining elements of learning outcomes related to subject matter. The two tests (intermediate and final), which were administered as a part of a set of online questionnaires, were designed to compare competency at CAD surface model interpretation before and after the introduction of negative knowledge within the newly developed integrated course structure. The tests were structured for participants to identify geometric deficiencies in surface models and provide an explanation for their evaluation. In particular, participants were asked to select one option out of five which, according to their best knowledge, most accurately described the geometric condition of each of the surface models in the questionnaires. Participants were also asked to rate their attendance at classes, for both lectures and exercises, as "all", "almost all", "less than half", "few", or "none". No time limit was imposed on the tests, as they were administered as a part of the voluntary anonymous online survey that was outlined earlier. Once the questionnaires had been submitted, participants were not able to review or change their answers.

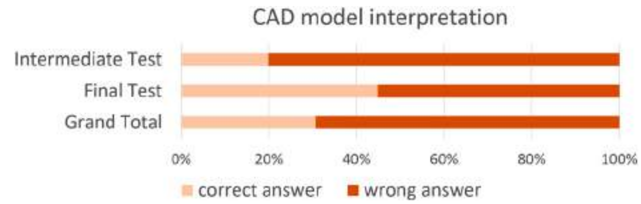

Figure 4. Graphical representation of proportions of correct and wrong surface model interpretation responses for the intermediate test and the final test.

4.3.1.1. Results and discussion. The online questionnaires were made available to 187 students who were currently enrolled in the course. The response rates were 67.4% for the intermediate survey and 51.3% for the final survey. Of the 222 completed surveys collected, 126 (56.8%) were from the intermediate survey and 96 (43.2%) were from the final survey. Evaluation of the CAD model interpretation section of the intermediate test resulted in 19.8% correct responses and 80.2% incorrect responses. Evaluation of the final test resulted in 44.8% correct responses and 55.2% incorrect responses. A graphical summary of these data employing a stacked bar chart (cf. [14]) is given in Fig. 4.

The proportion of correct answers improved considerably between the intermediate test and the final test (by a factor of 2.26), indicating an improvement in the capability of students to correctly perform a CAD surface model interpretation. This came about after the introduction of teaching methods based on negative knowledge. However, to determine the percentages of true correct responses based on actual know-how and skills, and not on fortunate coincidence, guessing right, etc., it requires, in addition, an assessment of the explanations associated with the answers in the tests. Therefore, supplementary statistics for CAD model interpretation responses in regard to subject matter consistency were calculated as shown in Tab. 1. In the case of the intermediate test, there was no statistically significant relationship between the model interpretation result and the accuracy of its explanation as given in the responses. However, in the case of the final test, a significant relationship between the accuracy rates of CAD model interpretation and the accuracy of explanation (Pearson's test of independence for $df = 1$, $\chi^2 = 19.499$, $p = 1.01e\text{-}5$) was detected.

These results further support previously indicated trends of performance improvement reflected, in the case of answers associated with correct explanations, not only by a considerable increase in the proportion of correct answers, but also by a considerable decrease in wrong answers, whereas, in the case of answers associated with inconsistent explanations, the proportions of both

Table 1. Proportions of correct and wrong surface model assessment responses for the intermediate test and the final test in relation to subject matter consistency of the explanation provided with each assessment response.

	Intermediate Test Responses		Final Test Responses	
	Correct Answers	Wrong Answers	Correct Answers	Wrong Answers
Consistent with explanation	7.1	35.7	26.0	8.3
Inconsistent with explanation	12.7	44.5	18.8	46.9

Table 2. Proportions of correct and wrong surface model assessment responses for the intermediate test and the final test in relation to attendance at classes.

	Intermediate Test Responses		Final Test Responses	
	Correct Answers	Wrong Answers	Correct Answers	Wrong Answers
All or almost all lessons attended	12.7	54.0	31.3	18.7
Half or more lessons skipped	7.1	26.2	13.5	36.5

correct and wrong answers did not exhibit a considerable change.

Another outcome measure related to test performance in respect to attendance at classes was pursued in order to shed some light on the impact of negative knowledge based teaching methods within the newly designed course. Proportions of CAD model interpretation responses in relation to attendance at classes were calculated as shown in Tab. 2. In the case of the intermediate test, there was no statistically significant relationship between the accuracy of the model interpretation result and attendance at classes. However, in the case of the final test, a significant relationship was detected between the accuracy rates of CAD model interpretation and attendance at classes (Pearson's test of independence for $df = 1$, $\chi^2 = 12.174$, $p = 4.85\text{e-}4$).

Also, in this case, the proportion of correct answers improved considerably between the intermediate test and the final test (by a factor of 2.46), while the proportion of wrong answers decreased in a similar manner by a factor of 2.89. This indicates an improvement in the capability of the students to correctly perform a CAD surface model interpretation, and this seems to be related to the rate of attendance at classes. It is reasonable to infer that a prerequisite for students to benefit from this newly designed course structure is that they attend classes and interact not only remotely with the learning material provided online, but also in person during laboratory exercises, in particular those in the second half of the course, where teaching based on negative knowledge is increasingly used.

4.3.2. Part II: Assessment of learning outcomes based on archival data

Aim and study design. This part of the multi-method study is aimed at determining aspects of competency development by examining elements of learning outcomes related to the creation of actual CAD models. This study is divided into two segments related to the type of archival data used for analysis, namely CAD models that were submitted in partial fulfillment of the requirements for the final exam of the course and CAD models that were created by students during laboratory exercises. In the case of the former, a CAD model type is used to indicate whether the model was comprised of two components, each created separately as a surface model and a solid model respectively (non-integrated CAD model), or whether it was one component, a final solid model that was obtained from a surface model created earlier (integrated CAD model). Note that students are free to decide on whether to submit a non-integrated model or an integrated model for the final exam. Integrated CAD models usually represent a simplified application of shape engineering, where students first have to design the aesthetic external shell of a consumer product, like a power drill, an electric kitchen mixer, or hair clippers, and then sub-divide the overall shape into individual components, which then have to be converted into a solid model with thickness, and to which functional features like mating lips, bosses, and ribs, must be added, as shown in Fig. 5. Due to their limited engineering domain knowledge and expertise at this stage of their education, students are required only to consider and manage geometric modeling related issues, without taking into account issues pertaining to the wider context of engineering design and actual manufacturing.

In order to approach an integrated CAD model project, students must have a fair understanding of the required skills and abilities. Not only must they be able to create a usable free form surface shell, but they must also convert this surface model into a solid model with appropriate geometrical properties. At the same time they must avoid reaching an impasse during model conversion due to deficiencies they unknowingly inflicted on the surface model in the previous process. In this regard, the total number of integrated CAD model projects submitted for

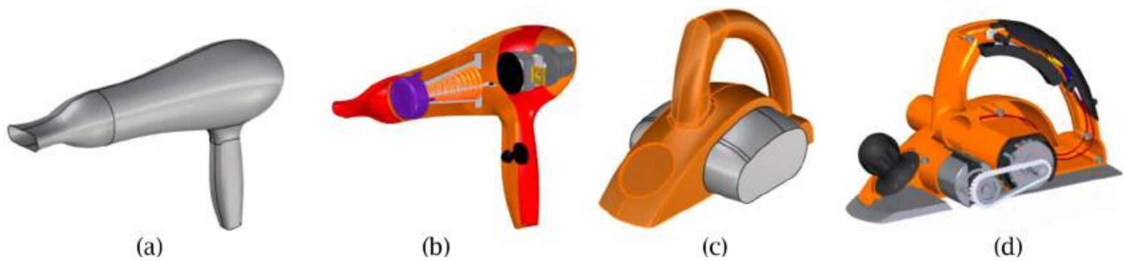

Figure 5. Examples of integrated CAD models submitted for the final exams in the academic year 2015/16. From left to right: (a) surface model of a hair blow dryer, (b) related solid model of the hair blow dryer with functional features added, (c) surface model of a portable hand power planer, (d) related solid model of the portable hand power planer with functional features added.

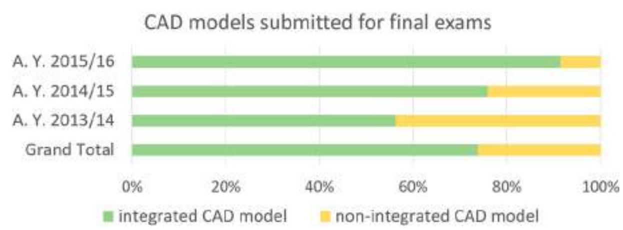

Figure 6. Graphical representation of proportions of integrated CAD models and non-integrated CAD models submitted for final exams in the past three academic years.

final exams can be seen as a kind of proxy for implicitly indicating the level of confidence and assumed competency of students in relation to learning outcomes from the course.

4.3.2.1. Results and discussion. Of the 355 CAD models selected and retrieved for analysis from the digital archives of the courses, 103 were from the final exams of the past three academic years and were used in the first segment of this second part of the study. The number of CAD models related to final exams for each academic year is as follows. 39 CAD models were from 2013/14, 29 CAD models were from 2014/15, and 35 CAD models were from 2015/16. A graphical summary of these data related to CAD model type is given in Fig. 6.

Note that the academic year 2013/14 was the last time the course was held in its previous unchanged style. In the academic year 2014/15, implementation of the newly developed course structure started. In the academic year 2015/16, restructuring of the course was completed and it took its current form. When we compare two consecutive academic years, there is no statistically significant relationship between the type of CAD model submitted for final exams and the academic year, i.e. the stage of development of the course structure. Perhaps this is due to the fact that elements of teaching method related to negative knowledge had already been partially implemented in 2014/15. However, if we compare academic year 2013/14 with academic year 2015/16, a significant relationship is apparent between the type of CAD model and the course structure, i.e. previous unmodified course vs. newly developed and fully implemented course (Pearson's test of independence for $df = 1$, $\chi^2 = 11.469$, $p = 7.08\text{e-}4$; Yates' correction $\chi^2 = 9.762$, $p = 1.78\text{e-}3$). As course records from previous academic years show, the proportion of integrated CAD models submitted for final exams always remained well below the two-thirds mark, in a manner very similar to the data reported for the academic year 2013/14. A noticeable increase in the proportion of integrated CAD models submitted for final exams started in 2014/15, with a jump from 56.41% to 75.86%. This was the academic year in which implementation of negative knowledge based teaching methods started. By 2015/16, the academic year in which implementation of negative knowledge based teaching methods was completed, the rate had reached an astonishing 91.42%. This is yet another example where empirical results are consistent with theory in that negative knowledge appears to support the formation of confidence, while also contributing to ability and skill development.

The second segment of this part of the study represents work in progress. Hence, results and discussions are limited to preliminary outcomes obtained prior to the writing of this paper. Analysis of CAD models created by students during laboratory exercises represents another valuable means of determining and analyzing competency development related to learning outcomes that are reflected in results of actual performance. Although this method offers considerable potential, before being able to tap into that potential one needs to overcome the complexity of individual CAD model assessment in regard to model deficiency and model usability criteria. To support model assessment in this direction, an experimental software tool for the detection of geometric deficiencies (for more details on geometric deficiencies see [19,28]) in surface models is currently being developed and has been partially implemented through modules programmed in Python. At present, for the academic year 2015/16, 252 CAD models stemming from six different exercise assignments are available for assessment. Note that submission of CAD models created during exercises is not mandatory. Hence, not every student enrolled in the course opted to submit, resulting in the noticeable difference between number of students enrolled in the course and actual number of exercise-related CAD models available for assessment.

Preliminary results of current efforts to assess individual exercise-related CAD models seem to be supportive of and consistent with observed tendencies related to competency development as follows. Analysis of geometric deficiencies in CAD models, which, in the case of open boundaries, was completed for all exercise-related CAD models, revealed that the majority of these deficiencies occurred in models linked to exercise assignments, which are associated with lessons where teaching employed mostly positive knowledge based methods. For example, this was the case for exercise assignments related to the modeling of a plastic beverage bottle and an eyeglasses case, where open boundaries were detected in 14.06% and 14.81% of the models. In exercise assignments that were associated with lessons where teaching made extensive use of negative knowledge based methods, such as during lessons on shape engineering and CAD model use, the proportion of CAD models flawed by open boundaries decreased considerably. For example, this was the case for exercise assignments related to the modeling of a trackball and a wall-mounted hand dryer housing, where open boundaries were detected in 10.20% and 4.88% of the models. As open boundaries in CAD models are a serious deficiency, which prevents the creation of a valid solid model based on the previously designed surface model, a considerable decrease in the occurrence of this model deficiency can be interpreted as a notable positive development in the ability and skills to create usable CAD models. Assessment of exercise-related CAD models in regard to degenerated patches, another severe geometric deficiency that is highly likely to prevent a surface model from being converted into a solid model, yielded, for the exercise assignment related to the modeling of a plastic beverage bottle and an eyeglasses case, an occurrence rate of 92.19% and 37.04% respectively. These results suggest that teaching which employs only methods based on positive knowledge is less effective in supporting competency development than teaching combined with methods based on negative knowledge.

4.3.3. Part III: Evaluation of self-assessment related to aspects of competency

Aim and study design. This part of the multi-method study is aimed at determining aspects of competency development by examining individual sentiments on subject knowledge, abilities, and skills acquired, in relation to indubitable performance as tested, and self-rated attendance rate at the classes and exercises. The two self-assessment surveys (intermediate and final), which were administered as part of a set of online questionnaires, were designed to compare self-rated competency with actual ability to correctly conduct a CAD surface model interpretation before and after the introduction of negative knowledge within the newly developed integrated course structure. The surveys were structured for participants to rate on a scale from 1 to 10, with 10 being the highest level, their current overall CAD competency (self-rated competency score *SCSo*). They also rated particular competency aspects in terms of ability and skill level in respect to planning properly and efficiently the modeling of a geometrically correct and usable surface model (self-rated competency score *SCSp*), rectifying an incomplete and defective CAD model (self-rated competency score *SCSr*), and being able to recognize and properly identify critical issues in a CAD model (self-rated competency score *SCSi*). This numerical score was converted to a competency level system consisting of five categories, namely "no level of competence", low level of competence", "average level of competence", "moderately high level of competence", and "high level of competence". Each category is associated with a numerical value pair on the rating scale with the smaller number representing the lower bound and the larger number representing the upper bound of the score range. For example, all self-rated competency scores in the range of 5 to 6 were associated with the category "average level of competence". As the self-assessment surveys were administered as a part of the voluntary online survey that was outlined earlier, the same conditions of conduct as in Part I, described above, were applied.

4.3.3.1. Results and discussion. Evaluation of self-rated competency scores obtained through the intermediate survey showed similar patterns for each of the various types of skills. 32% to 40% of students rated themselves of average competency and 25% to 35% rated themselves of low competency, except in the case of the *SCSi* group, where slightly more students believed that they had moderately high competency than low level competency. Percentages for the lowest and highest levels of competency remained below 16% and below 2.5% respectively. However, this pattern changed in responses obtained through the final survey. Now 57% to 63% were in the moderately high competency level. Only 7.5% were in the low level and 27.5% in the average level of competency. For the lowest and highest levels of competency, percentages remained below 7.5% and 6.5% respectively. A graphical summary of these data related to self-rated competency scores is given in Fig. 7.

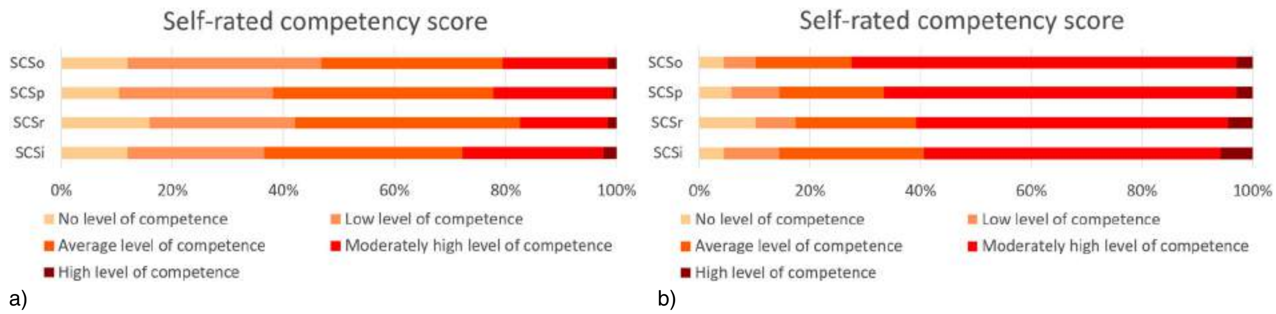

Figure 7. Graphical representation of proportions of self-rated confidence scores. From left to right: (a) intermediate survey, (b) final survey.

Improvement in self-rated competency score is most pronounced for *SCSp,* where 63.5% rated themselves as having at least a moderately high level of competency. This suggests that competency in planning the correct modeling of usable CAD models, and thus strategic knowledge development, has improved the most. *SCSi* had the highest level of students rating themselves at both the low level and the average level of competency. This skill group also showed the lowest increase in those who believed that they had at least a moderately high level of competency. Only 57.3% considered that they had reached that level, which was well below the rate of 68.7% in the overall group *SCSo*. Improvement seemed to have been recognized least within the *SCSr* group, which also contained the highest proportion (7.3%) of those who believed that they were still at the very lowest competency level, indicating that, according to student opinion, the competency to recover from mistakes and rectify erroneous and incomplete CAD models has developed the least. Overall, there had been an improvement in self-rated competency scores from the situation where the majority of the students believed that they possessed only a low or average level of competency to the position where the majority claimed at least a moderately high level of competency. This undoubtedly reflects a positive development, and it is not only a matter of subjective awareness, but an indication of actual progress made in know-how, skills, and abilities, which students have acquired through their learning experiences during the course. This in turn seems to be related to aspects of heightened individual certainty, increased efficiency, and improved ability to reflect. These are features that are encouraged and promoted by negative knowledge.

To advance insight on the relationship between competency development and teaching methods based on negative knowledge, as employed in the newly designed course, self-rated competency scores *SCSi* related to the interpretation of CAD models have been evaluated in relation to test performance and attendance rate at classes (for detailed discussion on these data see again Part I), yielding results as follows. Computed average $\overline{SCSi}$ of self-rated competency scores *SCSi* in regard to test performance, where answers could be associated with correct explanations obtained through the intermediate test responses, showed similar values (5.4 vs. 5.5) for correct and wrong answers, indicating that self-rated competency was at almost the same level for most students before negative knowledge based teaching methods were increasingly introduced into the course (cf. Tab. 3). This relationship had changed considerably by the end of the course, as data from the final survey and test show. In the case of correct answers, the average score increased to $\overline{SCSi} = 7.1$ and thus exceeded even the overall self-rated competency score average of all the final responses (6.65), while in the case of wrong answers the average score decreased to $\overline{SCSi} = 5.1$. On the one hand, this can be interpreted in respect to negative knowledge as a significant development of competency which is evinced not only in the higher-than-average increased performance outcome supported by increased certainty and efficiency, but also by an improved ability to reflect on one's own

Table 3. Arithmetic mean $\overline{SCSi}$ of self-rated competency scores *SCSi* for correct and wrong surface model assessment responses in the intermediate test and the final test taking into account subject matter consistency of the explanation provided with each assessment response.

	Intermediate Test Responses		Final Test Responses	
	Correct Answer	Wrong Answer	Correct Answer	Wrong Answer
Consistent with explanation	5.4	5.5	7.1	5.1
Inconsistent with explanation	4.9	4.7	6.3	6.7

knowledge, skills, and abilities, in an appropriate and more realistic manner, thus promoting development of both actual competency and the ability to self-rate it more reasonably. This line of interpretation is also supported by the improvement in the average of self-rated competency scores $\overline{SCSi}$ that were computed for correct test answers in relation to cases where all or almost all classes were attended. Results improved considerably from $\overline{SCSi} = 6.1$ in the intermediate survey to $\overline{SCSi} = 7.2$ in the final survey. On the other hand, there were some students whose learning progress, and thus competency development, were somewhat less strong, or who had failed to progress beyond a certain point. In some cases, disappointment in their personal performance may have led to an increase in classes missed, and thus exacerbated their problems. These students too were realistic and their self-rated competency did not develop beyond a certain level.

4.3.4. Part IV: Survey-based assessment of opinion on teaching methods related to competency development

Aim and study design. This part of the multi-method study is aimed at determining aspects of competency development by examining individual sentiments on teaching methods in relation to self-rated competency and actual performance as tested. The survey, which was administered as part of a set of online questionnaires, was designed to compare personal opinions on the importance and usefulness of teaching methods with both self-rated competency at and actual performance of correctly conducting a CAD surface model interpretation after the introduction of negative knowledge into the newly developed integrated course structure. In the opinion survey, within the online questionnaires, five options were given for expressing an opinion about teaching methods related to positive knowledge and negative knowledge as experienced during classes and CAD laboratory exercises within the newly designed course. The five options were as follows:

- Both tutorials and learning about errors are important, but learning about errors is more useful
- Both tutorials and learning about errors are important, but the tutorials are more useful
- Learning about errors is more important
- Learning with tutorials is more important
- Tutorials and learning about errors are equally important and useful

The survey was structured for participants to select the option that best described their opinion on the teaching methods used in the course in regard to importance and usefulness. As the opinion survey was administered as a part of the online questionnaires within the voluntary final survey that was outlined earlier, the same conditions of conduct as in Part I and Part III, described above, applied.

4.3.4.1. Results and discussion. Of the 96 complete responses that were collected from the final survey, 43 (44.8%) were linked to correct answers in the final test, while 53 (55.2%) were linked to wrong test answers (cf. data in Part I). Of the 43 responses, 44.2% believed that teaching methods based on tutorials and on knowledge about errors are equally important and useful. In the case of the 53 responses, the rate was 35.8%. In 32.6% of responses linked to correct answers in the test and in 18.9% of responses linked to wrong answers in the test, the opinion was that the tutorials and learning about errors are equally important, but learning about mistakes and what should be avoided is more useful. Employing only positive knowledge related teaching methods in the form of lectures and tutorials was thought to be important and useful by 4.7%, of those who provided correct test answers and 17% of those who gave wrong answers in the test. Teaching methods based only on learning about errors and mistakes was thought to be important and useful by 7% who gave correct test answers, and by 3.8% who gave wrong answers. A graphical summary of these data is given in Fig. 8. An overview of the results obtained from the survey relating to opinions on the importance and usefulness of various teaching methods in regard to the arithmetic mean $\overline{SCSi}$ of self-rated competency scores $SCSi$ for both correct and wrong test answers, is given in Tab. 4.

Overall results of the opinion poll suggest that, by the end of the course, the importance and usefulness of teaching methods related to both positive knowledge and negative knowledge had been realized by many students, independent of their actual performance in the test and their self-rated competency scores. There was a tendency to prefer teaching methods related to negative knowledge in the case of responses that could be linked to correct test

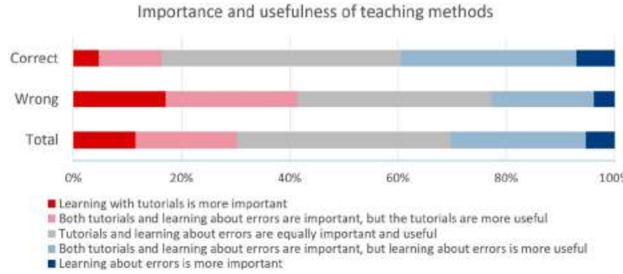

Figure 8. Graphical representation of proportions of opinions regarding the importance and usefulness of teaching methods in relation to correctly interpreting a test surface model.

Table 4. Opinions regarding the importance and usefulness of teaching methods in relation to correctly interpreting a test surface model and to the arithmetic mean $\overline{SCSi}$ of self-rated competency scores $SCSi$.

	Survey Responses (Correct Test Answers)		Survey Responses (Wrong Test Answers)		All Survey Responses	
	Frequency	$\overline{SCSi}$	Frequency	$\overline{SCSi}$	Frequency	$\overline{SCSi}$
Both tutorials and learning about errors are important, but learning about errors is more useful	32.6	7.3	18.9	6.9	25.0	7.1
Both tutorials and learning about errors are important, but the tutorials are more useful	11.5	6.2	24.5	6.2	18.7	6.2
Learning about errors is more important	7.0	6.3	3.8	6.0	5.2	6.2
Learning with tutorials is more important	4.7	6.5	17.0	6.0	11.5	6.1
Tutorials and learning about errors are equally important and useful	44.2	6.6	35.8	6.7	39.6	6.7

answers, and a preference for teaching methods related to positive knowledge in the case of responses that could be linked to wrong test answers. A weak statistical relationship could be detected between test performance results and opinions about the usefulness of teaching methods in the case of responses that acknowledged the importance of both teaching methods (Pearson's test of independence for $df = 1$, $\chi^2 = 3.876, p = 4.89\text{e-}2$). This supports the outlined tendency in this direction. However, more data is required to provide a more stable and conclusive assessment. Taking into account self-rated competency scores, the score average of all final survey responses (6.58) was closest to the average score of responses which stated that both teaching methods are equally important and useful. For responses that indicated a preference for teaching methods related to negative knowledge, the overall score was noticeably higher than the overall average score, while in all other cases the score average remained below the overall score average. However, when responses were grouped in respect to the performance outcome of the test, the situation was different. In the case of responses linked to wrong test answers, three out of five score averages $\overline{SCSi}$ were slightly below the group score average of 6.4, while in the case of responses linked to correct test answers, only two score averages were below the group score average of 6.76. Also the overall self-rated score average was slightly lower than the group score average for responses linked to wrong test answers. One possible explanation for this observation can be attributed to negative knowledge and expertise in that they represent an important component of competency, which in turn is reflected in better performance and a more adequate self-rating. Here the former is supported by an increase in certainty as a result of the acquisition of negative knowledge, leading to an awareness of possible positive as well as negative outcomes in regard to strategies and actions. The latter can be attributed to increased reflective capabilities, which are known to be promoted by negative knowledge.

5. Conclusions and future work

In this paper theoretical and practical issues have been outlined and discussed related to the actual implementation and empirical evaluation of a novel approach aimed at facilitating as well as improving competency development for product design within efforts to promote innovation in MCAD education. From a pedagogical viewpoint, the novelty of the approach is 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 and are related to experience from and reflection on errors, shortcomings, and mistakes which were encountered during assignments and work-related activities.

Theoretical evaluation and a first-time multi-method-related examination of empirical 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 substantially increased. This observation, among other issues, was reflected in data from self-assessment regarding CAD modeling skills and abilities, and laboratory exercises, which correlated with the suggestion that students had advanced in both positive and negative knowledge. The opinion poll administered within the final survey, regarding the two teaching methods integrated in the newly designed course structure, showed that the majority of students found teaching based on positive knowledge and teaching based on negative knowledge equally important. However, most students who showed a better test performance and a higher self-rated competency score found learning about errors to be more useful, while most students with lower test performance and a lower self-rated competency score found learning with tutorials more useful. Results and insight obtained are currently being used as constructive input to improve laboratory exercises and questionnaires for the next academic year. These efforts are intended not only to provide better support for learning outcomes, but also to further the collection of empirical data through the surveys. The surveys, in turn, by facilitating an increase in the quantity and quality of empirical data collected, will support the improvement of analysis and assessment aimed at allowing more statistical tools and evaluation methods to be applied.

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