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Parametric Feature-Based Solid Model Deficiency Identification to Support Learning Outcomes Assessment in CAD Education

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Abstract. New tools are needed to support CAD course reform efforts. These reforms aim to increase the development of strategic knowledge and modeling skills within CAD competency, and their implementation requires better structured and more frequent assessment and feedback. In particular, formative assessment and formative feedback are essential. Unfortunately, within CAD education, dedicated techniques and tools are not yet available to support the implementation of formative assessment, and, in particular, to assist learning goal and outcome-oriented assessment of CAD models produced by students. The aim of the current paper is two-fold. Firstly, it strives to present a novel approach for parametric feature-based solid model assessment in the educational context. This is based on deficiency analysis in relation to learning outcomes. Secondly, it reports on the implementation and application of a newly developed software tool module to enable and put into practice this novel CAD model assessment approach. The new module will be combined with a module for surface CAD model assessment to form an integrated semi-automatic software tool that is aimed at supporting assessment of both parametric feature-based solid models and surface models.

Keywords: formative feedback, reflection on performance and outcome, competency development, strategic knowledge build-up, geometric CAD model usability.
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1 INTRODUCTION

In many departments of science and engineering at institutions of higher education, didactic pedagogy is still the dominant and most common method of teaching CAD. This represents a traditional, behaviorism-oriented approach with the aim of providing students with basic knowledge and skills. In particular, within CAD education, the traditional approach to teaching is based on the use of tutorials and practical examples, along with definitions of guidelines and best practice. This is considered sufficient for building CAD models with specific CAD systems, representing the shape of a part subject to design. The content of the subject matter, as related to the modeling process, is broken down into individual behavioral steps reflecting algorithms needed to build the topology and geometry of the model and the sequences of commands to operate the CAD system accordingly. Therefore, it is supporting the deficiencies of modern CAD systems, which are heavily based on geometric modeling techniques. This is due to historical reasons related to the development of the design and the manufacturing processes that evolved around the geometric shapes of parts and products. In such a scenario of traditional CAD education, learning outcomes obviously lack the components that link different aspects of the CAD model created to actual design intent and the resulting model structure.

2 BACKGROUND, SCOPE, AND OBJECTIVES

2.1 Background and Related Work

Recent work in educational research has been aimed at creating awareness of and addressing the most prominent shortcomings and failures of current CAD education, among other issues. Such efforts have provided new insights and recommendations, although the work is still limited and the results sometimes contradictory. However, this approach is gradually increasing the empirical body of evidence for improvement, and moving steadily in the right direction. The need for educational exercises in the CAD laboratory, providing opportunities for students to experience both creation of their own models and the alteration of models created by others, is investigated and discussed in [21,26,39]. Work on promoting good design practice by relating model attributes to design intent can be found in [42]. There is demand for a change of focus in traditional CAD education from the declarative knowledge relating to geometric algorithms and commands required for operating a CAD system, in the literature referred to as *command knowledge*, toward knowledge and expertise which can transcend a particular CAD system. This is discussed, among other CAD related educational issues, for example, in [3,8,45,47,51]. This work highlights the need for higher level thinking relating to what is commonly known as *strategic knowledge*, i.e. knowledge of the different methods of achieving a specific task (goal) and knowing how to choose among those methods. Note that, in this context, design intent can be considered as falling under the category of strategic knowledge (see [10,15,25,26,29,39]). Moreover, as stated in recent work, for example, reported in [35], design intent is still "a nebulous concept" ([35], p.50), which makes it less effective and efficient to be explicitly employed. For several technical parts of the work presented in this paper, in particular the development of the software tool module, the more practice-oriented concept of alterability of feature-based CAD models for mechanical engineering was found to be more beneficial and appropriate.

Moreover, recent developments, stemming from both the results of cognitive science in education and changes in a progressively technology-influenced and increasingly complex global labor market, attest to the need for current efforts in restructuring curricula and integrating suitable elements of alternative teaching approaches to transform CAD education so that it is more student centered and learning as well as practice oriented. It needs to be better structured so that it efficiently and effectively matches actual student learning outcomes with skills and competencies related to, among other attributes, spatial ability and mental visualization, cognitive model composition, meta-cognitive processes including planning, predicting, and revision, and modeling strategies (see also [5,44]). How some of these challenges were addressed and tackled from various directions within discipline-based educational research is reported and discussed, for example, in [9,11,13,32,36,42]. Other recent work, including empirical research in this direction in both the Western and the Asian higher education context, can be found in [1,20,27,41,46,48].

2.2 Scope and Objectives

To translate the potential and benefit of those encouraging approaches into educational practice, however, also requires better structured and more frequent assessment and feedback than can be achieved with traditionally employed summative assessment and feedback techniques. Here, formative assessment and formative feedback appear to offer a viable solution (see also [22,24]), and these are increasingly regarded as promising and effective components within the instructional practices currently proposed for reforming higher education in science and engineering. Unfortunately, within CAD education, dedicated techniques and tools are not yet available to support the implementation of formative assessment, and, in particular, to assist the learning goals and outcome-oriented assessment of CAD models produced by students. Moreover, those frameworks and tools that are available for CAD model analysis and evaluation, and that are deployed within commercial and industrial settings, cannot be directly used in educational settings, due to differences in assessment criteria and evaluation goal settings. These differences focus mostly on issues related to application context, quality, and interoperability of CAD systems (see discussions and tool reviews in [18,19]).

Recent efforts to reform an actual CAD course, which is currently a part of the curriculum for the Laurea degree in mechanical engineering at the institution represented by the authors, addressed, among other matters, the development of modeling competencies with particular reference to the strategic knowledge required to create usable CAD models (see [36,37]). In particular, this major course-specific learning goal, i.e., development of the strategic knowledge and modeling skills indispensable for producing usable CAD models, requires better teaching techniques that reach beyond the usual lecture-based presentation of domain-specific factual knowledge with students mostly in the role of passive learners. Moreover, it especially requires assessment techniques and feedback which are capable of adequately and frequently measuring the gap between actual student learning outcomes as achieved and learning goals as pre-assigned, while also providing high quality and timely feedback for both teacher and students. Within this setting, and in the context of higher education, as outlined earlier, the assessment of student performance and results produced in CAD laboratory exercises and course assignments needs to be conducted in a computer-aided manner. This will support actual implementation, while also improving the scope and overall quality of formative assessment and feedback, but it requires new approaches and tools for feature-based solid model assessment. The aim of the current paper is, firstly, to present a novel approach to feature-based solid model assessment in the educational context, which is based on deficiency analysis in relation to learning goals and outcomes; and secondly, to report on the technical architecture and concrete implementation of a newly developed software tool to enable and put into practice this novel feature-based solid model assessment approach.

3 APPROACH, FRAMEWORK, AND IMPLEMENTATION

3.1 Outline and Approach

As pointed out above, inspection, analysis, and assessment of CAD models within an educational context are different from their (in somewhat reduced form) counterparts in commercial and industrial settings in regard to goal and assessment criteria definitions. This is most evident within formative assessment. To promote as well as advance formative feedback in CAD education, feature-based model and geometric model assessment needs to consider the quality of a model not only in terms of the absolute criteria that are associated with technical domain knowledge, but also by applying criteria related to model deficiencies that are the result of wrong or inappropriately applied system commands and partial or entire modeling strategies. This represents a task that is far from trivial, as assessment requires not only the detection and identification of deficiencies that in many cases do not violate general normative knowledge about feature-based modeling and geometric modeling (see also discussions on realism errors in [18]), but also knowledge about the modeling goals and how they have been translated into actions.

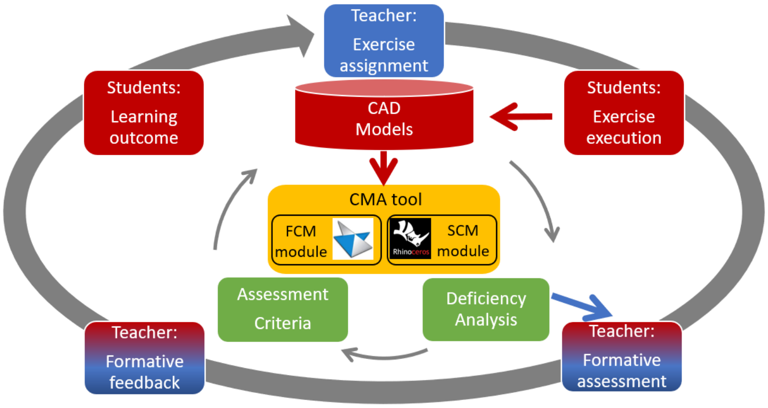


Figure 1: Overview of structural components related to CMA tool, deficiency analysis, assessment criteria, and formative feedback within the newly developed integrated CAD course.

Within an educational context, parts of the latter can usually be associated with learning goals and outcomes related to particular exercises and course assignments (see also overview as depicted in Figure 1). In the context of parametric feature-based solid model assessment, analysis and evaluation need to be based on both feature-related properties and characteristics and the topology and geometry of the final modeling result. In particular, properties of individual features and characteristics of feature sequences that were created for producing the final model shape can be used as a proxy for assessing particular modeling steps in a reflective and ex post facto manner. Currently, most commercially available CAD systems that support feature-based modeling provide interactive commands at the user interface to allow for some basic form of inquiry about model properties and the characteristics of both feature entities and topological/geometric model entities such as feature modeling tree, feature type, and related shape defining elements. However, performing a purely manual feature-based solid model assessment by using such kinds of generic system command is in many cases a sensitive task, which can devolve into quite a convoluted and time-consuming process. Moreover, only one model can be analyzed at a time. There is, therefore, a risk of putting in place different sets of assessments for individual models which were actually created for one and the same exercise or course assignment, and thus, in fact, relate to the same set of learning goals and outcomes.

3.2 Framework and Software Tool Development

To support parametric feature-based solid model assessment, while avoiding the shortcomings as outlined, a software tool in the form of a module for feature-based CAD model assessment (FCM module) has been developed. The module will be combined with a module for surface CAD model assessment (SCM module, previously also developed by the authors) to form an integrated semi-automatic software tool for CAD model assessment (CMA tool, see again Figure 1) that is aimed at supporting assessment of both feature-based solid models and surface models. The newly developed FCM module, introduced and outlined below, operates tasks in four process stages, namely compilation and export, import and filtering, enquiry and analysis, and visual analytics and assessment, as follows:

- All feature-based solid models that have been created by students are compiled and stored in a repository. This repository is structurally sub-divided into sets of different folders, with one set of folders for each exercise or course assignment. During the compilation process, information on feature entities and their related properties and meaningful characteristics, such as feature type, shape defining topology and geometry, is extracted from the parametric feature-based solid models, codified, and stored in the form of structured files, with one file for each model.

- Data on parametric feature-based model entities and their properties and characteristics stored in the model repository are processed and imported into a CAD model inventory. This CAD model inventory provides a lattice-based data structure, which is structurally organized as various linked entity tables. Data compiled from CAD models associated with a particular exercise or course assignment are assigned to one particular cluster of entity tables. It should be noted that table entries for each feature entity in the model repository contain also an identifier-based link, which connects them to the geometric modeling system. This link mechanism allows for the support of human-based visual analytics and assessment of entities within the original data source, namely the CAD models in the modeling environment.

- To facilitate the computer-aided search for and identification of deficiencies in feature-based CAD models, filter and query functions that are associated with the assessment criteria are provided at the user interface of the software tool. Those functions operate directly from the data of feature entities and their properties and characteristics, which were previously compiled and stored in the inventory. Note that the assessment criteria which are employed, are related to the expected learning goals and outcomes of the individual exercises and course assignments.

- Final overall assessment, which still requires human intervention and expertise, is supported by the model entity analysis results obtained in the previous task and the cross-link structure outlined earlier. The latter enables entities in the repository and the inventory to be connected with their corresponding entities in the modeling environment. Hence, each entity in question, and, most importantly, those found by the software tool to be deficient, can be located in the original CAD model and made visible for further inspection and assessment by a human expert such as the course instructor or the academic supervisor.

3.3 System Structures and Implementation

To facilitate integration with previous work of the authors on software assessment tool development (see [37]), the software tool design is based on a modular open system structure (MOSS), which operates through the CAD model and feature entity (CMFE) repository that in turn facilitates the import from and export to not only different parametric feature-based solid modeling environments, but also sets of linked feature entities (FEs) and reference feature entities (RFEs) used to identify deficient feature entities. Within the CAD model feature entity (CMFE) inventory these are then compiled together with results into the model entity analysis reports. The newly developed software tool features a technical architecture that leverages API-based functionality provided by commercially available CAD systems to support the modular and highly cohesive system architecture as shown in Figure 2. Within the current implementation, the modeling environment deploys a commercially available parametric feature-based solid modeling system, namely *SolidEdge* from Siemens AG. At present, the CMFE repository is compiled by extracting CAD data from the *SolidEdge* part models using VBA (Visual Basic for Applications) functions. This extracted data is then further processed and stored in structured *Excel* files. Next, those structured *Excel* files are imported into the Microsoft *Access* RDBMS (relational database management system) by means of macros, to facilitate the creation and built-up of the CMFE inventory. Assessment criteria used for the CAD model deficiency analysis are specified and implemented using a set of domain-specific *Access* queries.

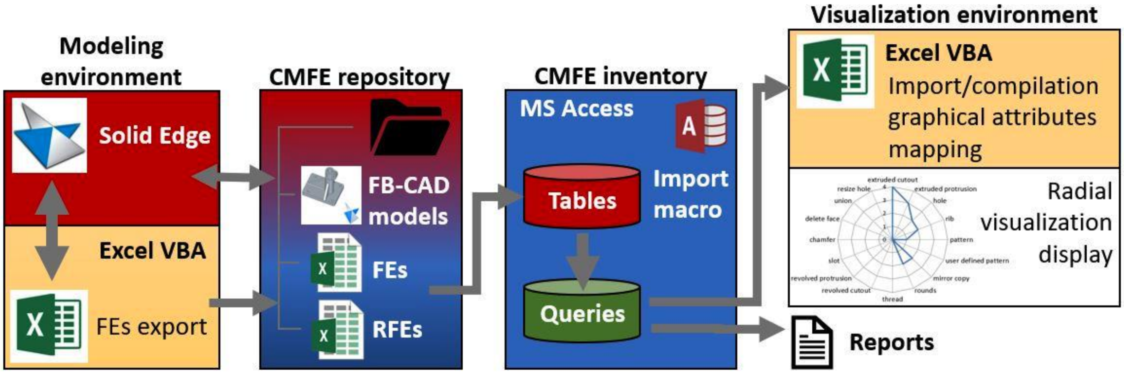


Figure 2: Overview of technical architecture of the FCM module and the visualization module that are an integrated part of the CMA software tool.

Visual analysis represents a powerful means of understanding complex data, as visual displays allow humans to make use of their cognitive capacity to perceive and study various aspects of complex information and issues simultaneously. To facilitate this, a modularized visualization environment (see again Figure 2) has been developed and integrated into the FCM module architecture. Although graphical representations are a comprehensive aid, their efficiency and effectiveness strongly depend on both the data to be visualized and the information to be communicated. Within the context outlined in this paper, a particular form of radial visualization is used, namely *Kiviat diagrams* [28], in the literature also referred to as *star diagrams* and *radar charts* (see [12,40]). With respect to CAD model deficiency analysis, the information subject to visualization is the relationships between and basic data for the feature types and the number of respective entities that were used to create CAD models. Based on this data, certain characteristics of trends, critical situations, and deficiencies can be visually highlighted. Current design of the Kiviat diagrams is structured by a vertical subdivision of the diagrams with the left half containing the mapping of data to graphical attributes regarding all features that should not be used, and the right half containing mapping regarding all the features that are recommended for the CAD model creation. Note that the order of the axes of the Kiviat diagram is relevant. In the current display layout, data extracted from a CAD model without any deficiencies, such as the CAD modeling exercise (CME) reference model (see Appendix A), result in a somewhat regular line profile shaped similar to either a capital P or a capital R, depending on which type of pattern feature was used (see details in the CME reference and the corresponding Figure A1 (c) provided in Appendix A). Note that all visualizations that refer to a CAD model without deficiencies in regard to the analysis criteria considered appear only in the right half of the diagram. Any deficiencies related to the presence or absence of certain feature types and the number of feature entities can then be made directly visible by certain shape distortions in the Kiviat diagram. Currently, the modularized visualization environment is implemented using the Visual Basic for Applications (VBA) environment and a data pipeline to the CMFE inventory that is channeled through compiled subsets of query reports.

4 EMPIRICAL RESULTS FROM EDUCATIONAL PRACTICE

4.1 Outline

Within the recently restructured MCAD course, various modeling exercises are provided employing a novel teaching approach that systematically utilizes negative knowledge in addition to traditional lectures and tutorials. Each of these modeling exercises addresses a particular learning goal. Outcomes of the exercises, in the form of CAD models created by students, are collected and analyzed, to identify shortcomings and errors which usually remain hidden from students due to their limited domain knowledge and expertise. Results are then used as input for formative assessment and feedback. Currently, a series of design and modeling exercises is being administered, where each exercise corresponds to the domain subject being taught within individual course units associated with it. The exercise assignments are designed to begin with a less complex design object, and gradually increase in complexity of modeling task and object shape according to progress made in the course and the domain subject being taught.

The newly developed FCM module for feature-based CAD model assessment, and its current prototype implementation that is now integrated into the CMA software tool, were successfully tested and validated using various feature-based CAD models, and these have been successfully compiled into a CMFE repository of feature entities. These feature-based CAD models were submitted by students as results of CAD laboratory exercises and course assignments administered within a CAD course for mechanical engineering that is offered by the department where the authors operate. The initial testing of the FCM module that is now a component of the CMA software tool and its application within the analysis and assessment of feature-based models covered all learning goal groups and related learning outcomes as stipulated for the course work. Validation of the FCM module in regard to accuracy and robustness in detecting feature-based CAD model deficiencies was carried out by human experts. In parallel with the application of the software tool, those experts also performed a manual inspection for each individual CAD model used during testing. In what follows, a summary is presented of how learning goals and outcomes related to positive knowledge and negative knowledge are formed and used to design the CAD modeling exercise reference (see Appendix A), which in turn is used for the specification and application of filter functions to detect feature-based CAD model deficiencies. Note that, due to limits regarding the length of this manuscript, presentation and discussion of selected material will be confined to one exercise consisting of two segments. This exercise relates to the modeling of a bolted yoke clamp mechanism for rod fastening, with stiffening ribs and a likewise bolted rectangular mounting base. Students submitted 85 CAD models during the first exercise segment and 36 CAD models during the second exercise segment, resulting in a total of 121 CAD models, composed of 1,957 feature entities.

4.2 Learning Goals

The main learning goals of the two-segment exercise presented and discussed as a representative example in this paper are as follows. Within the first exercise segment, students should learn how to plan and organize an appropriate modeling strategy to create a feature-based solid model of the subject of design, which is, for the exercise as outlined above, a bolted yoke clamp fastening mechanism with stiffening ribs and a rectangular base mount. To accomplish this task, students are supplied with information as follows. Firstly, information is provided regarding the raw shape and approximate geometric appearance the part is expected to have, and about the bounding dimensions of the component which is subject to CAD model creation during the exercise. Secondly, information is provided regarding some basic characteristics of the expected final assembly, which includes a graphical representation depicting how the final assembly is supposed to look as an expected result of the second exercise segment (see Figure A3(b)). Note that during the first exercise segment no further details are provided regarding the final shape and dimensions of the component to be modeled.

The modeling strategy should be designed to allow for an outcome that is the feature-based CAD model, which can be consistently and easily altered or adjusted to a change in model design requirements, taking advantage of the parametric feature-based model structure. Notice that the range of model design requirements here is limited to the scope of the exercise. The model also needs to be good enough to enable it to be used within exercises that are scheduled later in the course, where the computer-aided creation of technical drawings from CAD models is part of the requirement. Within the second segment of the exercise, students are provided with concrete CAD model assembly components and further details of model design requirements, which should enable them to adapt the previously modeled component, so that it fits the final CAD model assembly consisting of the previously modeled yoke clamp fastening mechanism, a component to attach the base mount, a rod, and a set of fixing nuts and bolts. During the two-segment exercise, students are required to submit two CAD models, that is one CAD model for each exercise segment. Ideally, the submission for the second exercise segment should be a parameter-based altered version of the CAD model that was created during the first exercise segment. However, partially remodeled and newly created CAD models are also allowed for submission during the second exercise segment. Within such an exercise setting, students should develop experience in and understanding of how to translate changes and refinements in model design requirements into parameter adjustments of their own previously created models. An important aspect here is that students should learn through experience how crucial and consequential a well-designed modeling strategy and properly encapsulated design intent are in this context. This includes their committing mistakes and reflecting on them, as well as learning from them, thus supporting the development of personal knowledge about the nature and impact various model deficiencies, which are usually the result of mistakes committed by students during design and modeling, can have on subsequent applications involving re-design and re-use of the CAD models. Students are explicitly informed about the learning goals and outcomes, those requirements, and the fact that they have to re-use their own CAD models created during the first segment of the modeling exercise. Another educational reason for engaging students in feature-based CAD model creation during early exercises in solid modeling is related to the goal of domain-specific concept development. As soon as possible, students should develop knowledge of what the various features represent, and what a solid model represents, in a given context, as a proper understanding of these fundamental concepts is one prerequisite for the successful development of strategic knowledge and CAD competency throughout the CAD course.

4.3 Learning Outcomes

It is important to note that learning outcomes are sub-divided according to the recently reorganized course structure (see [36]) into two groups, namely learning outcomes related to positive knowledge and learning outcomes related to negative knowledge. Negative knowledge is knowledge about what is wrong and what is to be avoided in certain situations. The course also builds on existing concepts of negative knowledge, as developed in research on expert systems, knowledge management, and professional learning, as well as on the development of expertise. For an overview and more details, see also discussions in [16,31,33,34,38].

Learning outcomes related to positive knowledge

Students should be able to design a modeling strategy that enables the creation of a parametric feature-based CAD model which can easily be altered through parameter modification to correctly fit as a component within an assembly and also be sufficiently structured to be re-used in other applications such as the computer-aided generation of technical drawings. To achieve this outcome, students must be capable not only of identifying the proper type and modeling sequence of features, but also of adequately defining the profiles, dimensions, and constraints that are used to implement the semantics and shape-related aspects of individual feature instances. This, in turn, requires the development of subject knowledge about the various characteristics of different feature types, their application context, and the methods of creating them by using various modeling commands and variations of input parameters for the same modeling command.

Learning outcomes related to negative knowledge

Students should have developed a capacity to recognize critical situations and model deficiencies related to the various characteristics of the features and the diverse methods of implementation which were used to create the CAD model. In particular, they should have mastered the art of recognizing and identifying deficiencies that may turn into serious model errors during later stages of the model creation or when a model is altered. Among those are, for example, features with profiles that either consist of more than four geometric entities or include rounds. Among the critical situations students should recognize are those which are most likely to introduce deficiencies into the model such as when a hole feature is located in the center of a round. This critical situation is usually the result of a feature dependency where a round feature is the progenitor, which should be avoided. In a similar way, situations where extruded protrusion features depend on extruded cutout features should be recognized as critical and thus better avoided.

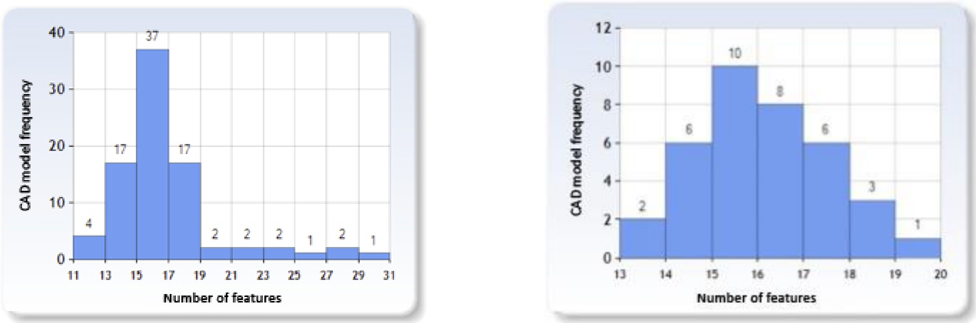
4.4 Model and Outcomes Assessment, and the Structuring of Feedback

4.4.1 Feature-based CAD model analysis. Part I: Overall analysis

In this first step within the overall analysis, all CAD models from both exercise segments need to be checked to see whether they contain features that have been recognized by the CAD modeling environment as being deficient. Note that, under the parametric feature-based solid modeling system currently in use, this condition can be detected and filtered by means of a query looking for records with a field value of the feature status that is neither 'OK' nor 'ROLLED_BACK'. Application of the filter functions in the FCM module analyzing the characteristics of feature entities in the CMFE inventory in regard to this condition returned, in the first exercise segment, 22 (1.58%) deficient features. These were found in 13 CAD models, with 3 cases marked as 'FAILED' (the system was unable to create the feature) and the remaining cases marked as 'WARNED' (the system was able to create the feature but some references were lost). Additionally, one suppressed feature (intentionally suppressed by the user) was found in one CAD model. FCM module analysis of the second exercise segment returned 13 (2.31%) deficient features. These were found in 7 CAD models with all cases marked as 'WARNED'. In most cases, a warning status is assigned to features when the profile loses its link to the reference geometry. This usually happens in cases where under-constrained features need to be regenerated when a CAD model is altered. Therefore, a higher proportion of deficient features with a warning status can be expected for the second exercise segment, which requires alteration of the CAD models that were created during the first exercise segment.

More detailed analysis revealed that the reason for the disappearance of both the deficient features marked as 'FAILED' and the user-suppressed feature, which were all detected in the first exercise segment but not in the second, was that all the CAD models which had originally contained those deficiencies had not been resubmitted for the second exercise segment. Those results seem to reflect on only a very small and limited scope of feature model deficiencies, which does not come as a surprise. As the authors have already pointed out, most software tools for CAD model analysis that are available and deployed within commercial and industrial settings cannot be directly used in educational settings. This is due to differences in assessment criteria and evaluation goal settings, focusing mostly on issues related to application context, quality, and interoperability of modeling systems (see [2,4,19,37,49,50]). Therefore, as the goal of CAD model analysis is to provide input for learning outcome assessment and formative feedback, additional CAD model analysis needs to be performed.

The next type of overall analysis that was carried out relates to the number of features used to create the individual CAD models during both exercise segments. The CAD models that were submitted during the first exercise segment required a total of 1,394 features, while the CAD models that were submitted in the second exercise segment required a total of 563 features. In respect to the number of CAD model submissions for each exercise segment, basic unimodal statistics are as follows. Regarding the first exercise segment, calculations revealed a mean μ = 16.4, a *mode* equal to 16, a *median* equal to 18, a standard deviation σ = 3.3684, and a standard error of the mean *SEM* = 0.3656. Regarding the second exercise segment, calculations revealed a mean μ = 15.6389, a *mode* equal to 15, a *median* equal to 16, a standard deviation σ = 1.4367, and a standard error of the mean *SEM* = 0.2394. The respective CAD model frequencies in regard to the number of features used for their creation are shown graphically in Figure 3. Statistical parameters such as the mean μ and the *mode* did not show much variation in the CAD model sets in respect to the number of features used in model creation, with around 15 to 17 features used in most models in both exercise segments. However, the standard deviation σ and the frequency tables, based on information computed by the filter functions of the FCM module, provided a more detailed and accurate view.



(a) (b)

Figure 3: CAD model frequency in regard to the number of features used for model creation. From left to right: (a) model frequency and number of features used in the CAD model submissions for the first exercise segment, (b) model frequency and number of features used in the CAD model submissions for the second exercise segment.

Here, the values of additional statistical parameters, together with the data represented in the histograms shown in Figure 3, indicate that the CAD models from the second exercise segment were far more coherent in regard to the number of features used to create them (see Figure 3(b)) than those from the first exercise segment (see Figure 3(a)). This fact is also reflected in the respective standard deviations, which differ by a factor of about 2.3, and in the number of distinct values, which was 7, covering a range of 13 to 19, for the second exercise segment (see again Figure 3(b)), while it was 15, covering a range of 11 to 30, for the first exercise segment (see again Figure 3(a)).

Next, within this first part of the overall CAD model analysis, investigation and assessment were carried out in relation to the proper renaming of features. The filter functions in the FCM module analyzed the characteristics of feature entities in the CMFE inventory in regard to features which had not been renamed. In the first exercise segment, there were 1,051 (75.39%) such features and in the second exercise segment, there were 334 (59.33%) such features. This difference indicates a possible relationship between the presence or absence of renamed features and whether a CAD model had been resubmitted for the second exercise segment or not. Additional filter functions were then used to take into account the frequency of CAD models that had or did not have an altered version resubmitted during the second exercise segment, while also checking on the presence or absence of renamed features in CAD models. The CAD model proportions were (56%,44%) for the former and (34%,66%) for the latter. Calculation of the ratio of probability based on a contingency table cross-product ratio, in the literature commonly referred to as an *odds ratio* (*OR*) (see [14,43]), yielded values as follows. The odds that CAD models that were resubmitted also contained renamed features were 1.3078. The odds that CAD models that were not resubmitted also contained renamed features were found to be 0.5278. This yields an odds ratio of $OR = 2.48$. Thus, according to those calculations, the overall odds that CAD models contained renamed features were almost 2.5 times as high for CAD models that had been altered and resubmitted during the second exercise segment as for CAD models that had not been altered and resubmitted. Here statistical analysis (Pearson's test of independence for $df = 1$, $\chi^2 = 3.891$, $p = 4.855\text{e-}2$) also yields a statistically significant relationship at the 0.05% level between the presence or absence of renamed features and CAD models having an altered version that was resubmitted in the second exercise segment. Hence, our previous assumptions are further strengthened. It seems that less deficient CAD models, indicated by the presence of renamed features, among other factors, are the most likely to be altered and subsequently resubmitted in the second exercise segment. A complete list of all not renamed features, their status, and their respective types, as detected, is given in Table B1 and Table B2 (see Appendix B).

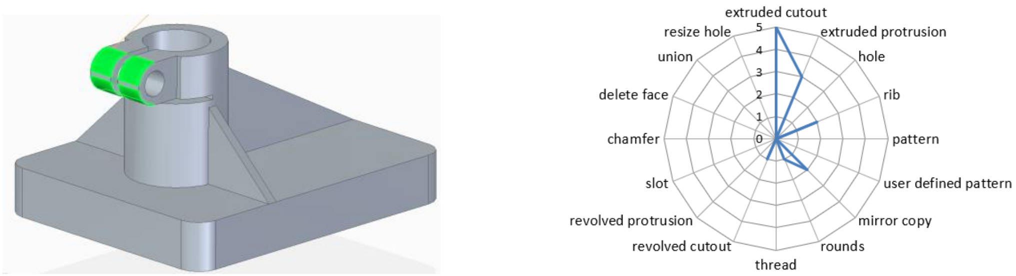
4.4.2 Feature-based CAD model analysis. Part II: Feature type compliance and CAD model completeness

Within this second part of the analysis, CAD models from both exercise segments were analyzed and assessed in regard to both feature type compliance with the CME reference and feature type related aspects of CAD model completeness. Features and feature types that are outside the scope of the exercise are termed *out of scope features* and *out of scope feature types*, respectively. Note that the scope related to subject matter, including feature types, is determined by the CME reference, which in turn is defined in regard to the content of an individual CAD exercise and the learning goal and learning outcomes associated with it. Filter functions in the FCM module analyzed the characteristics of feature entities in the CMFE inventory to determine whether their type was different from the recommendation in the CME reference. In the first exercise segment, 43 out of scope features were found in 22 (25.88%) CAD models. In the second exercise segment, 6 out of scope features were found in 5 (13.89%) CAD models. A complete list of all out of scope features and their respective types as detected is given in Table 1.

A more detailed analysis was then performed on the CAD models where out of scope features had been detected. Some examples of the results are as follows. Slot features were used instead of cutout features to create the jaw gap of the yoke head and the undercut of the yoke clamp. Revolved cutout features were also used in a similar vein in some models. Revolved cutout features were also used to model part of the yoke head as shown in Figure 4(a). Note that the model as depicted in Figure 4(a) actually contains several deficiencies, which are discussed elsewhere in this paper. In some CAD models, revolved protrusion features were used in attempts to create part of the yoke head, as shown in Figure 5(a). All these attempts have introduced a CAD model deficiency, because those feature types are not intended for use in such modeling situations.

Out of Scope Feature Types	First Exercise Segment	Second Exercise Segment
Chamfer	4	0
Delete Face	3	0
Resize Hole	0	1
Revolved Cutout	12	3
Revolved Protrusion	6	0
Slot	4	2
Thread	13	0
Union	1	0

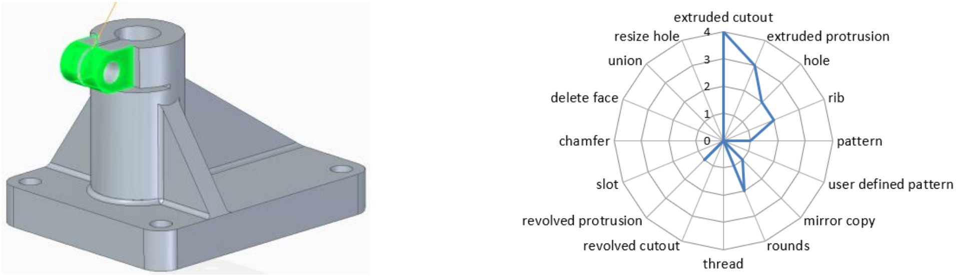
Table 1: Number of out of scope features that were detected in CAD models in relation to exercise segment and feature type.



(a) (b)

Figure 4: Example of actual CAD model containing out of scope features. From left to right: (a) model deficiency introduced by an inappropriate application of the revolved cutout feature, (b) related Kiviat diagram with an out of scope feature indicated by the presence of a revolved cutout feature.

A brief statistical assessment of the relationship between the presence or absence of out of scope features and CAD models that were resubmitted and those that were not, yielded results as follows. The odds that CAD models that were not resubmitted also contained out of scope features were 0.4474. The odds that CAD models that were resubmitted also contained out of scope features were 0.200, which yields an odds ratio of *OR* = 2.24. Thus, according to those calculations, the overall odds that CAD models contained out of scope features was almost 2.3 times as high for CAD models that had not been altered and resubmitted during the second exercise segment as for CAD models that had been altered and resubmitted. Again, these results point towards the tendency for CAD models that had been altered and resubmitted to contain fewer feature type related deficiencies.



(a) (b)

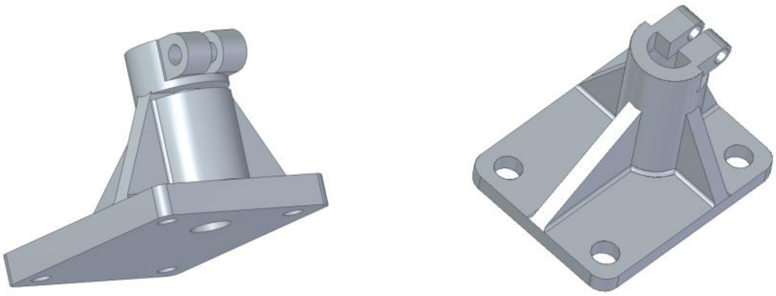
Figure 5: Example of actual CAD model containing out of scope features. From left to right: (a) model deficiency introduced by an inappropriate application of the revolved protrusion feature, (b) related Kiviat diagram with an out of scope feature indicated by the presence of a revolved protrusion feature.

The filter functions in the FCM module were then used to analyze the characteristics of feature entities in the CMFE inventory in relation to pattern features being used to model the circular passages for the bolted fixture in the rectangular base mount, and results were as follows. In the first exercise segment, 47 (55.29%) CAD models contained either a sound pattern feature with 4 entities based on a hole feature or a user defined pattern correctly modeled with an associated profile set based on 4 circular profiles. Analysis of the frequencies of CAD models containing a sound pattern for the 4 holes used for the bolted fixture of the rectangular base mount in regard to whether they did or did not have an altered version that was resubmitted for the second exercise segment, yielded proportions of 56.36% and 53.33%, respectively. However, in regard to imminent deficiencies, these results require a more detailed analysis of the remaining 38 (44.71%) CAD models. Deficiencies were most likely introduced by creating the pattern-based 4 holes of the base mount fixture with either a strategy not recommended, and thus falling short of the CME reference, or a flawed modeling approach causing faults in the CAD model. Another cycle of the FCM module-based checking system revealed that 7 of the 38 non-conforming CAD models contained patterns with 6 elements that were based on cutout features with a circular profile and that 3 CAD models did not contain any hole feature and had fewer than 3 cutout features with an associated circular profile. Detailed analysis revealed that in all of the 7 CAD models containing pattern features that were based on cutout features, 2 pattern entities were eventually suppressed. This indicates a serious deficiency in the understanding and use of the pattern feature, which is even more surprising taking into account that the number of holes required for the fixture within the rod fastening mechanism was given at the beginning of the exercise. The fact that those pattern features were based on circular cutout features instead of hole features can be considered a minor defect in this educational context. However, in a different setting, the use of a cutout feature instead of a hole feature as required might result in serious problems. For example, the dimensions of hole features relating to tool or part standards might be required for an efficient and effective model alteration, but they would not be available with certain feature types, such as cutout features. Deficiencies in the 3 CAD models lacking both a pattern feature and hole features were as follows. In two cases, the two detected circular cutout features were used to model two circular passages, one each for the rod and the yoke head. Additionally, it was found that in one of those cases the 4 holes required for the base mount fixture were not modeled at all (see Figure 4(a)), while in the other case those 4 holes were created as a part of the profile definition of the base mount. In a similar manner, in the third case, the 5 holes required for the bolted base mount fixture and the bolted yoke clamp were modeled as parts of the respective profile-based definition of the base mount and the extruded yoke of the clamp. Taking into account the frequency of CAD models that did or did not have an altered version that had been resubmitted during the second exercise segment, while also checking on the presence of deficiencies related to pattern features and hole features required for correctly modeling the circular passages of the base mount fixture, it was found that there was an odds ratio *OR* = 3.00. Again, this result supports the previously outlined tendency for CAD models that were altered and resubmitted to contain fewer deficiencies.

To further the assessment of CAD model completeness in regard to both exercise requirements and the CME reference, analysis was carried out on the explicit use of rib features instead of protrusion features or other means to create the ribs in the model. Application of the filter functions in the FCM module to analyze the characteristics of feature entities in the CMFE inventory in regard to rib features being used to model the central stiffening of the rod fastening mechanism, returned results as follows. In the first exercise segment there were 162 rib features, with 70 (82.35%) CAD models containing at least one rib feature, and in the second exercise segment, there were 67 rib features, with 29 (80.56%) CAD models containing at least one rib feature. Using additional filter functions to take into account the frequency of CAD models that did or did not have an altered version that had been resubmitted during the second exercise segment, while also checking the presence or absence of rib features in CAD models, CAD model proportions of (80%,20%) were found for the former, and (84%,16%) for the latter. Here the calculated individual odds yielded an odds ratio *OR* = 1.28. Thus, according to those calculations, the overall odds that CAD models contained at least one rib feature were only about 1.3 times as high for CAD models that had been altered and resubmitted during the second exercise segment as for CAD models that had not been altered and resubmitted. Therefore, in the case of the assessment of CAD model completeness related to the presence or absence of rib features, these results less strongly support the previously outlined tendency for CAD models that had been altered and resubmitted to contain fewer deficiencies. However, quite different is the case when the presence or absence of renamed rib features is analyzed in regard to whether CAD models were resubmitted or not. Here, with an odds ratio of *OR* = 5.71, the overall odds that CAD models contained renamed rib features were about 5.7 times as high for CAD models that had been altered and resubmitted during the second exercise segment as for CAD models that had not been altered and resubmitted. Here statistical analysis (Pearson’s test of independence for $df = 1$, $\chi^2 = 9.9904$, $p = 1.574e\text{-}3$) also yields a statistically significant relationship at the 0.05% level between the presence or absence of renamed rib features and CAD models having an altered version that was resubmitted in the second exercise segment. Note that the statistical calculations as presented were adjusted by taking into account the case of one CAD model that contained both one renamed and one not renamed rib feature.

To complete the analysis of CAD model deficiencies in this second part, previously obtained data and results regarding the number of features and feature types used to create models were combined and cross-examined. Here, a more detailed analysis was conducted of the reasons for the higher deviation in the number of features used per model in the CAD model submissions for the first exercise segment. This revealed that in CAD models with fewer features, usually the number of feature types used was also low, and fewer than the number recommended in the CME reference. However, in many cases, this deficiency did not reveal itself in visible shortcomings and defects in the overall model shape. This situation can be attributed in most cases to an unusually high number of geometric entities in the feature associated profile definitions. In some respects, this tended to compensate for the shortcoming in the number of features used, but then it caused other model deficiencies that are discussed in more detail in other individual assessment parts. However, some CAD models with low numbers of features and feature types exhibited visible defects. Those defects were related, for example, to the absence of some basic CAD model elements that were a part of the exercise requirements, and were revealed by considerable deviations in some parts of the CAD model shape.

For example, one CAD model that was created using only 14 features (see again Figure 4(a)) did not contain the four circular passages required for the bolted fixture of the base mount. Although this model used 6 different feature types, essential feature types such as a pattern feature and a hole feature were absent, while other types of features that should be avoided were used instead.

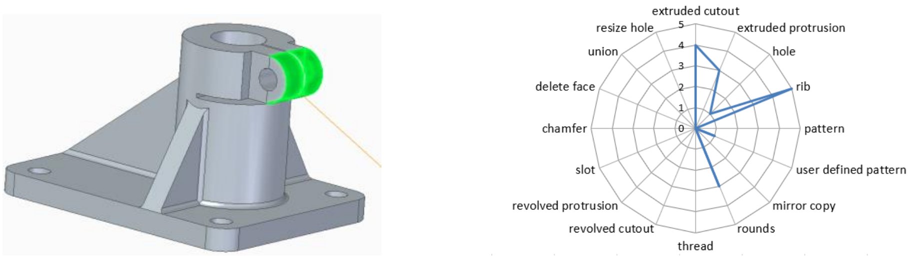


(a) (b)

Figure 6: Example of actual CAD models containing shape-related deficiencies. From left to right: (a) wrongly created horizontal cutout within the yoke clamp, (b) partially covered circular passage of the rod fastener.

In another case, a CAD model that was created using a mere 12 features was found to contain a major defect in the shape of the yoke clamp, as shown in Figure 6(a). The CAD model shown in Figure 6(b) was also found to contain a serious flaw related to the shape of the circular passage for the rod fastener. This CAD model also lacked essential feature types such as a pattern feature and a hole feature. Note that all CAD model deficiencies related to model shape were detected by analyzing results generated by the FCM module based on the number of features and feature types, without deploying any of the traditional topology or geometry-based feature recognition techniques.

In many cases, CAD models with a high number of features were found to contain several additional features of types such as revolved cutout or protrusion and delete face. These are either not recommended or to be avoided altogether. The number of features used was also found to be abnormally high in cases where there was a shortcoming in the modeling strategy. This was indicated, among other factors, by the absence of a pattern feature, resulting in a high number of extruded cutout features being used to model each individual passage of the base mount fixture and the yoke clamp. Cases were also found in which additional model entities had been created with features that were not part of the exercise model requirements. Examples of this were a fourth stiffening rib, chamfers, and threaded holes, which were present in the model although not required as part of the exercise.



(a) (b)

Figure 7: Example of actual CAD model containing a yoke head that was created in part with two rib features. From left to right: (a) use of two rib features to create part of the yoke head, (b) related Kiviat diagram with an unexpectedly high number of rib features.

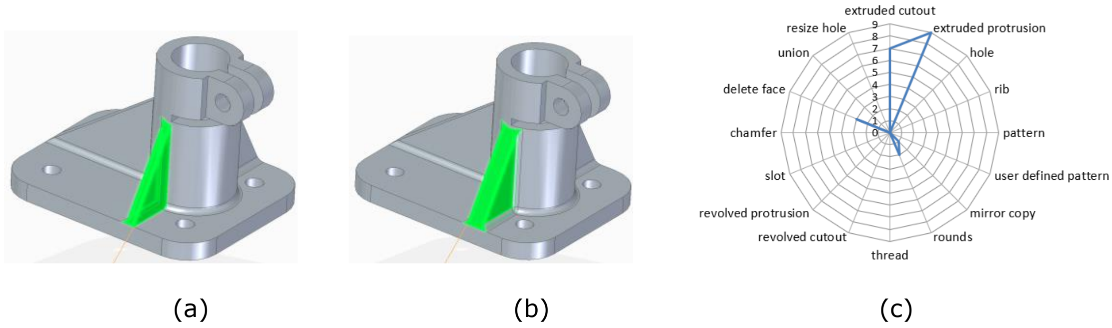


Figure 8: Example of actual CAD model containing stiffening ribs that were each created with two extruded protrusion features. From left to right: (a) initial use of an extruded protrusion feature to create the first half of a lateral stiffening rib, (b) repeated use of an extruded protrusion feature to create the second half of a lateral stiffening rib, (c) related Kiviat diagram with an unexpectedly high number of extruded protrusion features.

Analysis of CAD models with an unusually high number of features compared with the feature types expected, revealed that those features were used in inappropriate modeling or application contexts to create the required parts of models. For example, two rib features were used to create the outer rim portions of the yoke head, as shown in Figure 7(a). In another case, to create the stiffening ribs, two extruded protrusion features were used for each rib, as shown in Figure 8(a) and Figure 8(b).

4.4.3 Feature-based CAD model analysis. Part III: Modeling sequence compliance and dependencies between features

In order to improve the alterability of CAD models, dependencies between features should be limited as much as possible. Therefore, modeling guidelines aimed at supporting this goal recommend that all volume-adding features should be created before adding any volume-removing features to the CAD model. Among all the various types of feature dependencies considered possible, dependencies on round features and chamfer features are particularly critical due to two application or modeling context issues. Firstly, round features and chamfer features often need to be suppressed to adapt the CAD model structure to the requirements of particular applications, such as FEM analysis. In such a case, the suppression of those features can remove the reference geometry that is linked to a child feature, resulting in a warning or even an incorrect regeneration of the child feature. Secondly, if child features are located in the center of a round feature they depend on, any changes in the round radius are propagated, and subsequently alter the spatial location of those child features. Within this third analysis part, CAD models from exercise segments are analyzed and assessed regarding both feature modeling sequence compliance with the CME reference and also in view of relationships and associations between features, as well as between features and geometric entities. In regard to the CME reference, a correct modeling approach and its related feature sequence should begin with the creation of either a cylindrical extruded protrusion feature or a rectangular extruded protrusion feature, which should be associated with one profile consisting of not more than 4 geometric entities. Analysis of the feature sequences of the CAD models revealed that the first feature of all models was a rectangular extruded protrusion feature. This indicates that all students started model creation with the rectangular base mount. Further filter functions in the FCM module were then applied to analyze the characteristics of the first feature entities of the feature sequences in the CMFE inventory in regard to the number of both associated profiles and associated geometric entities. This analysis returned deficiencies in 14 CAD models as follows. In two cases it was found that the first feature in the modeling sequence contained 5 profiles instead of one. In the remaining 12 cases, the first feature had a profile associated with more than 4 geometric entities.

Detailed analysis of the two cases with multiple profiles revealed that in both cases, 4 profiles, each associated with only one geometric entity, were used to create the 4 cylindrical passages for the base fixture, while one profile, associated with 4 geometric entities, was used to create the rectangular base block. Detailed analysis of the remaining 12 cases revealed the causes of deficiencies as follows. In the case where one profile was associated with 5 geometric entities, the rectangular base block was created using 4 two-dimensional line entities and one construction line entity. Note that the use of the latter in this modeling situation is inappropriate. In the 10 cases where one profile was associated with 8 geometric entities, the rectangular base block was created using 4 two-dimensional line entities and 4 two-dimensional arc entities. In the case where one profile was associated with 9 geometric entities, the rectangular base block was created in a manner identical to the previous 10 cases. Here, however, an additional geometric entity was used, which was apparently the result of splitting one of the line entities into two line entities. A brief statistical assessment of the relationship between whether or not the first feature in the CAD model feature sequence was correctly modeled, in respect to the characteristics of its associated profile and geometric entities, and whether CAD models were resubmitted or not, yielded results as follows. The odds that the CAD models that were resubmitted did not contain a deficient first feature can be determined by the probability ratio, calculated as 9.00. The odds that the CAD models that were not resubmitted also did not contain out of scope features were found to be 4.00, which yields an odds ratio of OR = 2.25. Thus, according to those calculations, the overall odds that CAD models contained a deficient first feature were almost 2.3 times as high for CAD models that had not been altered and resubmitted during the second exercise segment as for CAD models that had been altered and resubmitted. Again, these results support assumptions about the tendency for CAD models that had been altered and resubmitted to contain fewer deficiencies relating to the beginning of the CAD model feature sequences.

Relationships between features that add volume and features that remove volume (see CME reference) were examined next. Note, in this analysis context, that deficiencies usually arise when CAD models contain volume-adding features which depend on features that remove volume. Application of the filter and query functions in the FCM module, in regard to volume-adding features being dependent on volume-removing features, returned results as follows. In the first exercise segment 71 (83.53%) CAD models contained volume-adding features dependent on volume-removing features, while in the second exercise segment there were 18 (50%) CAD models with this kind of deficiency. Using additional filter functions that also take into account the frequency of CAD models that did not have or did have an altered version resubmitted during the second exercise segment, returned CAD model proportions of (90.91%,9.09%) for the former and (70%,30%) for the latter. Here the calculation yields an odds ratio OR = 4.29. Thus, the overall odds that CAD models contained volume-adding features dependent on volume-removing features were about 4.3 times as high for CAD models that had not been altered and resubmitted during the second exercise segment as for CAD models that had been altered and resubmitted. Here, statistical analysis (Pearson's test of independence for $df = 1$, $\chi^2 = 6.1686$, $p = 1.300\text{e-}2$) also yields a statistically significant relationship at the 0.05% level between the presence or absence of volume-adding features dependent on volume-removing features and CAD models having an altered version that was resubmitted in the second exercise segment. Hence, assumptions are further strengthened in regard to the previously found tendency for less deficient CAD models, here indicated by their not containing any volume-adding features dependent on volume-removing features, to be altered and subsequently resubmitted in the second exercise segment.

Next, CAD model deficiencies related to round features were analyzed. In general, modeling situations that include the presence of any features depending on a round feature can be considered critical and should be avoided. The filter functions in the FCM module were again used to analyze the characteristics of feature entities in the CMFE inventory, now in regard to the presence or absence of feature relationships indicating a dependency on round features. Results were as follows. In the first exercise segment 47 (55.29%) CAD models were found to contain at least one feature that depended on a round feature, while in the second exercise segment there were 3 (8.33%) CAD models detected with this kind of deficiency. Additional filter functions were used to take into account the frequency of CAD models that did not have or did have an altered version that was resubmitted during the second exercise segment, while also checking for the presence or absence of feature relationships indicating a dependency on round features. CAD model proportions of (58.18%,41.82%) were found for the former and (50%,50%) for the latter. Here the calculated individual odds yielded an odds ratio *OR* = 1.39. Within this context, a particularly serious type of deficiency caused by round feature dependency occurs where particular types of features, such as hole features, pattern features, and user defined pattern features, are involved. This is usually the case for very critical situations when, for example, a hole feature is located in the center of a round feature, because any change in the round radius will ultimately result in a spatial relocation of the hole feature. In a similar manner, this also applies to pattern features and user defined pattern features. With a focus on hole features, pattern features, and user defined pattern features, a check was carried out as to the presence or absence of feature relationships indicating a dependency on round features in the CAD models, and found CAD model proportions of (13.33%,86.67%) for the former and (25.45%,74.55%) for the latter. The calculated individual odds yielded an odds ratio *OR* = 2.67. Thus, the overall odds that CAD models contained a deficiency that was related to the general presence of a round feature dependency were about 1.4 times as high for CAD models that had not been altered and resubmitted during the second exercise segment as for CAD models that had been altered and resubmitted. In cases where such a deficiency was related to hole features, pattern features, and user defined pattern features, the overall odds were about 2.7 times as high for CAD models that had not been altered and resubmitted during the second exercise segment as for CAD models that had been altered and resubmitted. Therefore, in the case of CAD model deficiencies related to the presence or absence of round feature dependency, these results again support the previously outlined tendency for CAD models that were altered and resubmitted to contain fewer deficiencies.

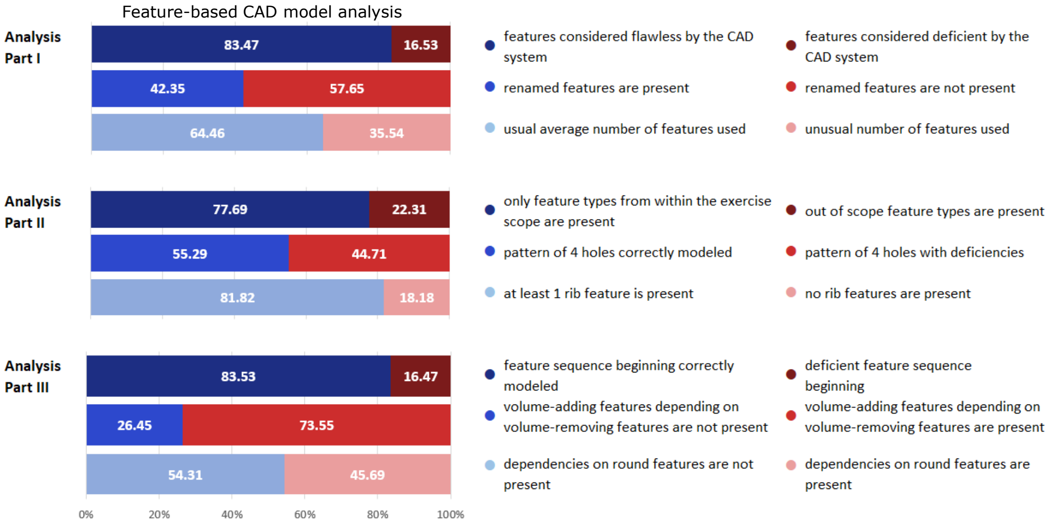


Figure 9: Graphical representation of proportions of CAD models and their deficiencies in each of the main categories corresponding to CAD model analysis part I, part II, and part III.

Figure 9 presents a graphical summary of the proportions of CAD model deficiencies which fall into each of the main categories as discussed above in the three-part CAD model analysis. This summary is in the form of a stacked bar chart (see [23]). At this point it is useful to recall that the main directions of CAD model analysis are determined to a large extent by the projected learning outcomes and exercise requirements, as the context of analysis and assessment is within CAD education, which differs in several aspects from the industrial and commercial context, as outlined elsewhere in this paper.

4.4.4 Feedback scaffolding and input for course and FCM module improvement

Within the educational context, feedback is one of the most powerful influences on learning and competency development. As feedback is an integrated part of the teaching and learning process, it needs to provide information specifically relating to the processes and tasks of learning to reduce the gap between what is understood and what is aimed to be understood (see [22,24,44]). Feedback is considered to be most effective, while also leading to greater student engagement and increased achievement, if it is provided extensively and is specific to tasks, indicating how to perform better and more effectively. Within the formative feedback framework, as developed for the recently restructured CAD course (see [36]), currently three dimensions are addressed that correspond with the focus at which feedback is directed (see also discussions in [22,24]). The nature and some basic characteristics of those three dimensions can be outlined as follows.

The first dimension of the feedback is related to information provision about the solution that was created during a task. In the given context, this represents the CAD models that were created by students for this two-segment exercise. Here the focus is mostly determined by the main learning goal and the learning outcomes related to positive knowledge as described elsewhere in this paper. Results from the assessment presented earlier that are relevant for this dimension of the feedback can be compiled into information on what kinds of errors have been introduced into the CAD models, what are the most likely causes of them, and, related to this, where and how improvement can be approached from the viewpoint of a student's learning efforts and experience. The examples encountered during analysis can be ordered into three groups as follows. Firstly, there are omissions which relate to elements such as hole features and rib features that were missing in the set of four holes for the base mount fixture and the set of three stiffening ribs. Secondly, there are extra unwanted elements, which are entities such as chamfers, threads in holes, and a fourth stiffening rib. Thirdly, there are shape deviations in parts of the CAD model, such as an incorrectly modeled yoke clamp (see again Figure 6(a)) and a partially covered circular passage (see again Figure 6(b)). Note that extra unwanted elements may appear visually as departures from the shape required, but they are conceptually different from shape deviations. In general, all these cases can be used to remind students about the incompleteness of the solution they have created in regard to the exercise requirements, which in turn have been designed according to the learning goals and outcomes. Here also some advice is in order to remind students that features are a combination of shape and engineering meaning that relate to the design intent and the mechanical functionality of the CAD model that has been created. Even in cases where students are not able to fully comprehend all the functional aspects of a mechanical device subject to the modeling exercise, at least some efforts should be made to avoid serious shape deviations in the CAD model. The quality of the solution produced, i.e. the CAD model created for the exercise, can be improved considerably simply by avoiding those errors outlined above, and that can be achieved through double-checking what has been created and comparing it with what was supposed to be created.

The second dimension of the feedback is related to providing information about the strategy and processes used to create the solution, in two steps as follows. Firstly, there is the initial design and modeling employed to produce a CAD model according to the exercise requirements. Secondly, there is the requirement to alter the previously created CAD model in a manner which will make it a fitting component in an assembly. Here, the focus is determined by the main learning goal and in some part by elements of the learning outcomes related to both positive knowledge and negative knowledge. Mistakes and errors regarding the process of creating CAD models can be attributed to shortcomings in know-how on the proper use of commands in respect to the modeling task being considered, and strategic knowledge as planned and employed. Concrete instances relating to the former are the inept and faulty attempts to create the set of four holes for the base mount fixture with a pattern feature consisting of 6 entities, which then requires two of the entities to be suppressed. Also, inappropriately revolving a cutout, that is, using a revolved cutout feature instead of an extruded cutout feature to create parts of the bolted yoke clamp, can be added as a further example. However, in this case, deficiencies could also relate to strategic knowledge. Students may focus more on the feature type and wrongly perceive the modeling requirements, rather than focus on the operation or command which determines how to implement the cutout. Concrete examples relating to the latter are attempts to incorrectly model stiffening ribs with extruded protrusion features. In some of the worst cases, students even used two extruded protrusion features to model one stiffening rib (see again Figure 8), employed slot features to model basic cutouts, and used rib features to model parts of the yoke head (see again Figure 7(a)). Also, the use of additional features, such as circular extruded cutout features, to mend the CAD model by attempting to undo shape-related errors (see again Figure 6(b)), can be added as a further example. Those errors, derived from the assessment of CAD model deficiencies in relation to the creation process, can be translated into formative feedback information in the form of recommendations and some more specific advice. For example, in cases where there are errors in the modeling approach, such as where ribs and parts of the yoke clamp were modeled using a faulty strategy, information can be given on what is wrong and some advice offered on alternatives to remedy the situation. This can include, for example, recommendations on how to replace some faulty sections of the modeling sequence or feature tree with their correct counterparts consisting of appropriate feature types and modeling commands. Sometimes mistakes were made in using individual modeling commands within a correct modeling strategy, resulting in a defective model. Examples are the case of revolving a cutout feature, which should be avoided in this exercise, and pattern features consisting of more entities than required. In these cases, concrete advice can be given on both the nature of the mistake and corrective measures to be taken. Deficiencies related to feature dependencies on rounds, and volume-adding features depending on volume-removing features represent concrete examples that relate to shortcomings in negative knowledge, as they create critical situations that can quickly turn into serious CAD model errors, as is typical for conditions such as CAD model alterations, which were required in the second exercise segment. Feedback needs to remind students of the learning goals and outcomes related to competency development, in particular negative competency and knowledge on what not to do, and how to recognize critical situations and thus avoid committing mistakes typical for novices. Here formative feedback information is partly intertwined with elements of the third dimension of feedback as discussed in the next paragraph.

The third dimension of feedback is related to information provision about self-evaluation, confidence, and the skill and competency development associated with them. Supporting students in developing negative knowledge and expertise is an important component within overall competency development. Advancing a novice's development of negative knowledge not only improves the ability to correctly self-evaluate, but also increases confidence, because, in addition to knowing what to do and how to do it, the student also gains knowledge in parallel about what not to do under certain conditions, as discussed, for example, in [16,33,36,38]. Regarding the concrete examples discussed within the second dimension of feedback, to elaborate more on the feedback focus toward what not to do in certain situations and to provide know-how on recognizing critical situations and thus providing ways of avoiding repetition of those mistakes, information can be given as follows. For example, in regard to the correct modeling of rounds, again information can be provided explicitly on what not to do to avoid critical situations in this particular modeling context. This may include a reminder that profiles should not include rounds and features should not depend on round features. Feedback should relate to critical situations and deficiencies in regard to volume-adding features that depend on volume-removing features, and additional advice can be offered as part of a critical situation description with pointers to related elements within positive knowledge such as recommendations for modeling strategies that add all volume-adding features before considering volume-removing features. This advice can then be combined with guidance on how not to create modeling sequences or feature trees that contain round features in positions other than at the end.

Besides providing input for feedback, the detection and assessment of deficiencies also offers valuable input for improvement of both the CAD course and the software tool. In the case of the CAD course itself, detection and assessment of mistakes that were beyond the scope of those usually encountered with the exercise and are thus to be expected, provided valuable input for guiding efforts to enhance the material contents used for the course lectures and also to improve the exercises related to feature-based modeling. Concrete cases of modifications made include, for example, improvements aimed at material related to the teaching of positive knowledge, where the material and the emphasis related to the concept of features, particularly basic feature types including rib and slot, have been re-arranged. Another example is improvements aimed at material related to the teaching of negative knowledge and critical situations and deficiencies that are related to the use of round features and the handling of critical dependencies between volume-adding features and volume-removing features. Improvements are in progress to the situation boxes (see [36]), which are used to teach know-how on recognizing critical modeling situations and what not to do in those situations. Also, the structure and contents of feature-based exercises such as the rod fastening mechanism, which was presented in this paper, have been revised to improve actual learning outcomes related to the correct application of basic feature types, and know-how on the correct command use for and actual modeling of feature patterns, and how to better recognize and avoid critical situations caused by certain feature dependencies as discussed elsewhere in this paper.

In the case of the FCM software module, detection and assessment of deficiencies that were beyond the scope of what is usually encountered with the exercise, as reported in each of the analysis parts, provided some guidance for the improvement of current filter functions and queries, as well as the design of additional functions. These will be better capable of performing a focused search of the CMFE repository for those newly identified deficiencies. However, this step requires first an improvement in the data extraction and compilation processes within the modeling environment and the CMFE repository. This is necessary to provide a wider range of information containing data with increased depth regarding profiles and constraints that can be extracted from the CAD model data structure, which is administered by the CAD system that is employed within the modeling environment.

5 CONCLUSIONS AND FUTURE WORK

Within work presented in this paper, the approach, structures, and technical architecture developed and used for the design and actual implementation of an innovative software tool module have been outlined and discussed. The modularized tool is aimed at supporting a learning outcomes-oriented assessment of feature-based models within the context of CAD education. This novel approach is based on the computer-aided detection of deficiencies in CAD models created by students as an outcome of modeling exercise assignments. The software tool module is developed and implemented with a modular open system structure, a CMFE repository, and a CMFE inventory, which allow for consistent and robust integration with a previously developed module to form an integrated semi-automatic CAD model assessment tool for both featured-based models and surface models. A compiled selection of examples was given to illustrate the translation and application of central concepts of the framework and the technical architecture of the software tool module and how these relate to and interact with exercise-specific learning goals and outcomes and the assessment of actual CAD models as created by students according to concrete exercise requirements. Within an actual educational context the test and evaluation of the experimental prototype of the software tool module produced valuable and encouraging theoretical and empirical results. Those were supportive in several ways for the shaping and advancing of insight, while also providing pointers for future work, some examples of which are as follows.

Detection and assessment of several deficiencies in CAD models created by students stemmed from, among other things, shortcomings in their understanding of domain subject matter relating to the concept of features and their meaning in regard to mechanical engineering. That became evident through cases where certain feature types were used in an inappropriate modeling context. For example, slot features and rib features were used instead of extruded cutout features and extruded protrusion features. Assessment of the CAD model analysis results also revealed that students had difficulty in properly creating and then using certain types of features, for example pattern features, in their modeling strategies, since these were perhaps too complex for novices. In this regard, shortcomings also became evident in their knowledge of what not to do and their being able to recognize critical situations during the modeling process. Among other cases, deficiencies related to feature dependencies regarding rounds, and deficient modeling sequences producing feature relationships where volume-adding features depended on volume-removing features, were detected in many CAD models. These results led to the consideration of reviewing and revising some parts of the lectures regarding the presentation and focus of fundamental domain concepts, such as features, within the solid modeling context. Hopefully, this partial reorganization, currently under way, of the lecture material taught in the CAD course, will further improve competency and skill development related to both positive and negative knowledge. In particular, improvements are planned in the teaching of the relationships between modeling goals and the use of feature types in regard to the planning of correct, effective, and efficient modeling strategies. In this regard it should be remembered that two-segment exercises related to feature-based modeling, like the one presented in this paper, were designed to let students have first-hand experience, combined with formative feedback, in facing various issues related to CAD model alterability. This was organized by requiring that they alter their own previously created CAD model in a manner which would make it a fitting component in an assembly. For the development of CAD competency it is important that students acquire an understanding about the role which modeling strategies have in regard to model alterability, taking into account that different modeling strategies may result in different CAD models with an identical shape, but that some models can be efficiently and effectively altered, while others cannot.

Future work regarding the CMA tool, and in particular the FCM module, is aimed at the improvement of both the framework and the software tool implementation. The detection of several quite unusual deficiencies in the student-created CAD models indicates a need to extend the current framework in regard to methods and definitions currently used to search for deficiencies. In particular, during tool-supported CAD model analysis and assessment, the application of the FCM module prototype has repeatedly shown that the range, depth, and type of information extracted from the CAD model data structure, which is administered by the CAD system, has a considerable impact on the functionality and implementation of filters and queries and their ability to identify critical situations and deficiencies. This applies even in cases that were quite beyond the range of known student mistakes and model defects usually encountered with the exercise. Therefore, efforts to improve both the framework and the software tool implementation require first an improvement in the data extraction and compilation processes within the modeling environment and the CMFE repository. Efforts in this direction, currently planned, seem to be most promising in regard to information that is related to profiles, and constraints among both features and their associated reference geometry. Finally, based on experience with and evaluation of the experimental prototype system, and also taking into account results obtained so far, preparations are under way to fully integrate both the module for feature-based CAD model assessment and the module for surface CAD model assessment and deploy the resulting integrated software tool as soon as possible within the recently reformed CAD course in mechanical engineering. Here, priority is being given to the facilitation and full support of timely and high quality formative assessment and formative feedback.

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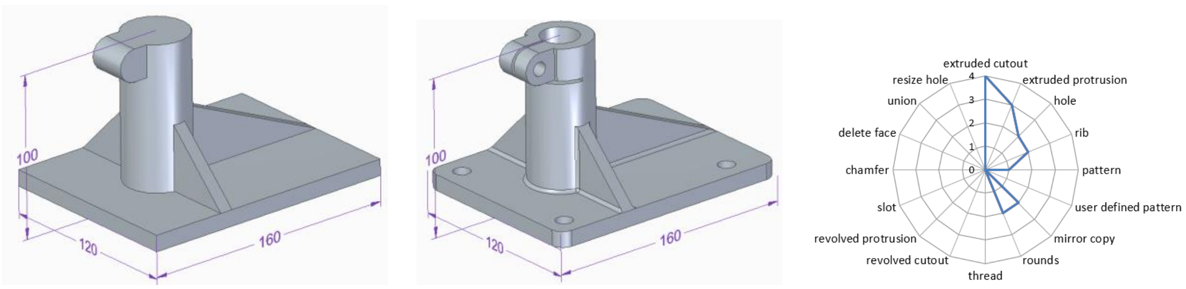
Appendix A

This appendix provides a detailed description of the CAD modeling exercise (CME) reference. For the most part, the CME reference consists of three basic components, namely the reference modeling approach, the reference CAD model, and the reference deficiencies. Those reference structures are used as a means of embodiment of information and knowledge about important facets of the basic goals, outcomes, and concepts and methods that are relevant for each individual exercise. The CME reference serves, among other functions, as a backdrop or foundation, which provides a reference for a domain and problem space. In the case of an ill-defined problem space (see [17,30]) such as computer-aided design, this is of considerable value for various purposes, especially for the assessment of produced outcomes.

The Reference Modeling Approach

Within the CME reference, the actual reference modeling approach is structured in the form of template solution, aimed at providing a means of affording a reference frame on know-how for correctly putting individual elements of strategic knowledge and modeling command application together. In the first segment of the exercise, the design of a proper modeling strategy requires the identification of all the features required for creating a CAD model of the rod fastening mechanism and the order of their implementation and application within the feature modeling sequence.

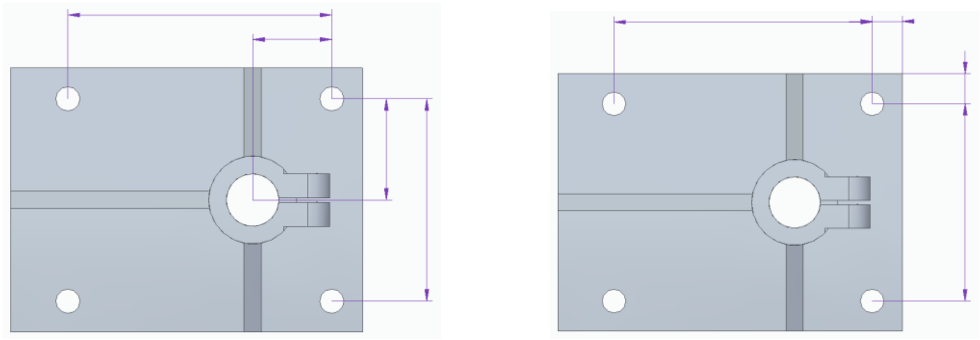
In general, there are several feature modeling sequences that can result in a valid CAD model that conforms to the shape and geometry of the CME reference model. However, within the educational context of this exercise, students are required to take into account elements of modeling guidelines and best practices as taught in the course lectures. Those include, for example, creating the full volume first, then all the cutouts, and leaving the creation of rounds until the end of the modeling sequence. In Figure A1, an example is shown of two possible stages of a correct modeling sequence. Among the various modeling strategies possible, one that is effective, efficient, and considered to be adequate as a reference within the given educational exercise context leads to a model creation that requires 16 principal individual features (see Figure A1(c)), from which a proportion of 75% should be constrained. These features can be defined and implemented by using just 7 basic feature types in combination with 12 profile sets and 18 dimensions.



(a) (b) (c)

Figure A1: Presence of features and basic dimensions at two different modeling stages in respect to the reference modeling approach. From left to right: (a) initial modeling stage with the CAD model consisting of protrusion features only, (b) final modeling stage with the reference CAD model and all of the features used to create it, (c) related Kiviat diagram indicating the number and type of all the features used to create the reference CAD model.

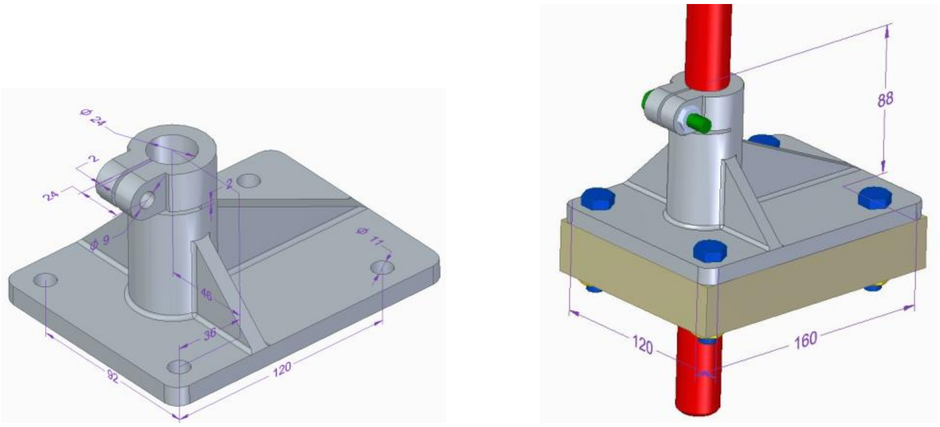
In addition to determining all the types of features and the order and relationships required for proper model creation, it is also important to choose appropriate methods, constraints, and dimensioning schema for the creation of actual instances of individual feature types. For example, to spatially locate and properly dimension the pattern of four circular holes in respect to the central rod fastening element, regardless of the actual values required for the final dimensions, the dimensioning schema as shown in Figure A2(a) is recommended. This, in turn, requires that, within the feature modeling sequence, the feature instances used to model the rod passage precede the feature instances used to model the passages of the bolted fixture of the rectangular base mount. A different dimensioning schema, as shown in Figure A2(b), which is not based on these recommendations, will require additional effort and most likely cause difficulties during model alteration in the second exercise segment.



(a) (b)

Figure A2: Dimensioning schemas for the pattern of hole features. From left to right: (a) proper dimensioning schema for the pattern of hole features in respect to the reference modeling approach, (b) dimensioning schema better avoided for the pattern of hole features.

The second segment of the exercise involves the creation of an altered version of the feature-based CAD model created during the first exercise segment. This should require only the modification of some model parameters related to the spatial location and dimensions of a few features, as follows. To properly align the five circular passages required for the bolted fixture of the base mount and the rod with their counterparts in the assembly's main base (see Figure A3(b) colored in beige), the locations of the hole within the cylindrical element and the four holes for the base mount need to be adjusted, and their dimensions need to be revised to accommodate the diameter of the actual rod (see Figure A3(b) colored in red) and the four hex head bolts (see Figure A3(b) colored in blue). Finally, the diameter of the horizontal hole in the yoke clamp head needs to be altered to accommodate the dimensions of the actual hex head bolt (see Figure A3(b) colored in green) that is used, together with a hex finished nut, to allow for effective fastening of the rod.



(a) (b)

Figure A3: CAD model altered in respect to the reference modeling approach for the second exercise segment. From left to right: (a) feature-based CAD model with final dimensions adjusted to fit requirements for the assembly, (b) assembly complete with all components in regard to basic dimensions as specified in the exercise requirements.

The Reference CAD Model Assembly

The CME reference CAD model refers to the first exercise segment and the actual CAD model created according to the modeling approach as outlined within the reference approach. The reference CAD model assembly refers to the second exercise segment and the altered version of the previously created CAD model of the rod fastening mechanism (see again Figure A1(b)), which is now a component of the assembly (see again Figure A3(b)). It also contains modeled components representing the actual rod, and the various nut and bolt sets used for fixing and fastening, as provided to the students in a neutral CAD format and described elsewhere in this paper.

At this point it needs to be made explicit that, once the types of features have been determined, together with the basic outline of the feature modeling sequence required for the creation of the CAD model, there are still some variations possible, although the range of these is limited. Such variations might eventually result in an outcome, perhaps less efficient and robust, but which could still be considered valid according to the CME reference.

The Reference Deficiencies

CME reference deficiencies are structured as a form of information and knowledge repository of what can go wrong during a modeling exercise and what kinds of errors are most likely to be committed by novices, and subsequently translate into known deficiencies being inflicted on a CAD model. Some examples to illustrate the nature and composition of this reference structure can be outlined briefly as follows. As the examples discussed in this paper are related to an exercise that is part of the course where solid modeling and feature-based modeling are introduced, one can expect students, being actual novices, to have some difficulty in avoiding shortcomings and deficiencies. In a parametric feature-based CAD model, most of the shortcomings and deficiencies known within the educational context as outlined can be related to the following particular aspects and characteristics of the model.

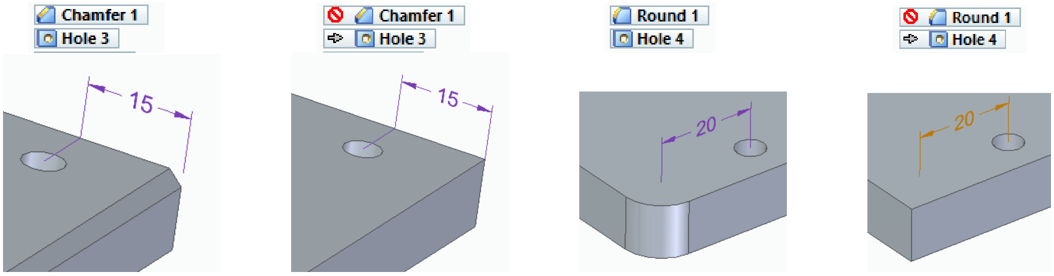
1. Deficiencies related to the presentation of the model, such as those shown in the feature tree
2. Deficiencies related to the sequence of features, that is the modeling sequence that leads to the final shape of the CAD model
3. Deficiencies related to the number and type of features used to create a portion of the CAD model shape and its related engineering meaning
4. Deficiencies related to the dependencies between features
5. Deficiencies related to the properties of the 2D profiles used to create features

1.) Deficiencies related to the structural feature-related presentation of the CAD model, which is usually expressed in the form of a feature tree. The feature tree not only represents the modeling sequence, but also provides the means for allowing the user to identify and access specific portions of the CAD model shape. This is required, for example, to perform model re-design and model alteration. Here the 'readability' of the feature tree is considered a central aspect of the 'easy-to-alter' CAD model. Therefore, the renaming of features is a minimum measure to ensure a certain readability of the feature tree. Deficiencies in regard to feature renaming, such as features retaining their generic name as automatically provided by the modeling system, can be expected. As observed in many exercises, this is partly due to a tendency for students to constantly underestimate the importance of meaningful and consistent feature renaming. This is considered by students to be a somewhat dull and wearisome activity compared to other modeling activities. Additional aspects within this type of reference deficiency are related to the number of features with an error or warning status and the number and proportion of fully constrained features and under-constrained features. In general, well-defined CAD models should not contain any features that have a status marked as error or warning. Also, renamed features and constrained features should represent the large majority of features used to create the CAD model. However, due to their lack of experience, students usually underestimate the importance of such requirements, especially while performing within the context of educational exercises, where the impact of such deficiencies on the result is less serious than in an actual work-related context.

2.) Deficiencies related to the sequence of features, which is the modeling sequence leading to the final shape of the CAD model. Here, deficiencies are often indicated by the unusually high number of features used to create the CAD model, in respect to the reference model, and this is usually related to shortcomings in the modeling strategy. It can be indicated, for example, by the use of *undo features* (see also further references and discussions on design reusability, the resilient modeling strategy, and the use of undo in feature-based CAD in [6,7]), which are employed to mend a CAD model after deficiencies have been introduced through previously committed modeling errors. The use of additional features may also indicate a deficiency in regard to the feature sequence. This type of deficiency appears when students start modeling with inadequate feature types or non-optimal sequences of extruded protrusion features and extruded cutout features. In general, by comparing the number and type of features used to create the CAD model with those used in the CME reference, it is possible to identify those models that deviate from the results expected, and thus require a more detailed analysis in regard to eventual shortcomings and deficiencies.

3.) Deficiencies related to the number and type of features used to create individual parts of the CAD model and related shapes. The CME reference model shows the number and type of features necessary for a correct model. Based on heuristics and experience from previous exercises, it is also known which errors are most likely to be committed that will result in deficiencies in this regard. They include, for example, holes created with circular cutouts instead of the hole feature, and ribs that are created with extruded protrusions instead of the rib feature. Where out of scope feature types or an unusual number of a particular feature type are used to create the CAD model, these new cases are analyzed and then added to the heuristics. In general, the presence of out of scope features in a well-defined CAD model is an indicator of an inappropriate modeling strategy.

4.) Deficiencies related to the dependencies between features can be critical and are best avoided. Feature dependencies are considered critical when changes in the parent feature have an adverse impact on the child feature, resulting in deficiencies being introduced into the CAD model. Although the situations where feature dependencies can be considered critical are various, some of the most common are known, because they have been encountered frequently in educational settings and have occurred in many previous exercises. These include cases, where, for example, the design depends on the use of chamfer features or round features.



(a) (b) (c) (d)

Figure A4: Dependency on chamfer features or round features is best avoided. From left to right: (a) hole feature with reference geometry depending on a chamfer feature, (b) hole feature with lost reference geometry due to dependence on a suppressed chamfer feature, (c) hole feature with reference geometry depending on a round feature, (d) hole feature with lost reference geometry due to dependence on a suppressed round feature.

In particular situations, certain feature types are suppressed during CAD model optimization processes. For example, in finite element mesh (FEM) operations, features depending on chamfer features (see Figure A4(a)) and round features (see Figure A4(c)) may lose reference to their associated geometry, as shown in Figures A4(b) and A4(d). This in turn results in child features being labeled as warned and rendered unstable.

(a) (b)

Figure A5: Dependency on round features is best avoided. From left to right: (a) two hole features with reference geometry depending on a round feature, (b) two hole features depending on a round feature are spatially relocated due to altered reference geometry caused by a change in the parameter value of the round feature.

In the case of dependency on round features, as shown Figure A5(a), a change in parent feature parameter values results in the recalculation of the center of the round feature, and consequently of the reference geometry. Quite unexpectedly for the novices involved, an alteration in the spatial location of the child features, that is the two hole features, is then triggered by the CAD modeling system, as shown in Figure A5(b). In general, features can be sub-divided into volume-adding features, such as rib features and various types of protrusion features, and volume-removing features, such as hole features, slot features, and various types of cutout features. In addition, round features are intended to be used at the end of a CAD model creation. Deficiencies such as those outlined above can be detected by examining the CAD model for feature dependencies. In particular, volume-adding features might depend on volume-removing features and attention should be given to whether any features depend on round features.

5.) Deficiencies related to the properties of 2D profiles used to create features. For novices, the creation of a correctly structured and fully constrained profile is no trivial task. Therefore, under-constrained profiles frequently occur in the feature-based CAD models produced during the exercises. When the alterations to the CAD models include changes in dimensions, under-constrained profiles become quite a critical issue due to profile re-generations that may result in unexpected impacts and even inconsistent shapes. It is important, therefore, to check that profiles are fully constrained (see also paragraph 1 above), but additional analysis related to geometric (profile) characteristics can also be performed as follows. As the CME reference model provides an indication of the number of dimensions that we can expect to be present in the CAD model, even sub-dividing them by feature type, searching for specific types of profile elements that we should expect to be present or absent is feasible. For example, the presence of arcs with small radius in the profile of an extruded protrusion feature would be an indicator of the creation of embedded rounds, which represents a situation that should be avoided. Note that this type of profile-related CAD model analysis is made possible by the application context, that is the educational exercise setting where the exact shape and conditions of the modeling result are known.

Appendix B

This appendix provides a complete list of all not renamed features, their status, and their respective types as detected by the software tool module.

Feature Type	Total	Status Not Ok		Not Renamed	
Chamfer	4	0	0.00	4	100
Delete Face	3	0	0.00	3	100
Extruded Cutout	350	9	2.57	258	73.71
Extruded Protrusion	305	6	1.97	213	69.84
Hole	138	1	0.72	108	78.26
Mirror Copy	81	1	1.23	60	74.07
Pattern	43	0	0.00	31	72.09
Resize Hole	0	0	0.00	0	0.00
Revolved Cutout	12	0	0.00	9	75.00
Revolved Protrusion	6	0	0.00	6	100
Rib	162	0	0.00	123	75.93
Round	244	4	1.64	198	81.15
Slot	4	0	0.00	2	50.00
Thread	13	0	0.00	13	100
Union	1	0	0.00	1	100
User Defined Pattern	28	1	3.57	22	78.57

Table B1: Number and proportion of features and deficiencies in relation to feature type as detected in CAD models submitted during the first exercise segment.

Feature Type	Total	Status Not Ok		Not Renamed	
Chamfer	0	0	0.00	0	0.00
Delete Face	0	0	0.00	0	0.00
Extruded Cutout	158	8	5.06	93	58.86
Extruded Protrusion	124	2	1.61	75	60.48
Hole	48	2	4.17	25	52.08
Mirror Copy	35	0	0.00	22	62.86
Pattern	17	0	0.00	7	41.18
Resize Hole	1	0	0.00	1	100
Revolved Cutout	3	0	0.00	2	66.67
Revolved Protrusion	0	0	0.00	0	0.00
Rib	67	1	1.49	36	53.73
Round	96	0	0.00	63	65.63
Slot	2	0	0.00	0	0.00
Thread	0	0	0.00	0	0.00
Union	0	0	0.00	0	0.00
User Defined Pattern	12	0	0.00	10	83.33

Table B2: Number and proportion of features and deficiencies in relation to feature type as detected in CAD models submitted during the second exercise segment.