Formative Feedback Improvement in MCAD Education: Supporting Knowledge-Driven Dormant Deficiency Detection and Analysis

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Abstract Currently, most software tools and educational interventions supporting the automated grading and assessment of CAD models, such as are currently provided to students in CAD courses, are limited by their metrics and by their assessment approach. In particular, the metrics they use are of a rather static and exclusive nature, relying heavily on the final outcome. That is to say that they rely upon the completed CAD model, which then has its data structure compared to that of a fixed reference solution. Such approaches are not structured suitably to assess CAD model quality in regard to robustness and alterability, due to their static and exclusive nature, which usually leads them to discount CAD model regeneration processes and their impact after alteration. To address those shortcomings while improving the learning experience, in particular supporting students in acquiring the knowledge and skills development needed to create robust alterable CAD models, among other issues, the dormant deficiency concept and metric and a software-based feedback agent have been developed. These were introduced recently during the restructuring of a mechanical engineering CAD (MCAD) course. To translate the insight from lessons learned into improvements of and support for this feedback intervention, a two-step project follow-up was initiated, with results from the first step being reported in this paper.

Keywords: Computer-based feedback provision, skill and competency development, student self-assessment, dormant deficiency, design intent, CAD model alterability and robustness.
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1 INTRODUCTION

Many experts consider formative feedback to be a crucial element of appraisal and evaluation in the learning process. Its potential for improving performance and enhancing learning outcomes is widely acknowledged in most fields and disciplines. However, as studies on the effectiveness and usefulness of feedback interventions have demonstrated, educational intervention is complex and does not always guarantee the pedagogical success expected (cf. [13,15,33]). With the increasing popularity of online course provision and e-learning environments in higher education, the implementation and provision of feedback based on software tools and digital systems is rapidly gaining traction (cf. [1,19,29]). With those computer-based approaches, personalized and immediate feedback can be provided at levels that are not feasible through human-based agents in traditional educational settings (see discussions in [30,34]). This is especially the case for introductory CAD courses, where the number of students tends to be quite high as those courses increasingly move into the curriculum of basic undergraduate education in various disciplines. Although structuring and providing feedback appropriately in a computer-based environment poses considerable challenges (cf. [18,28]), there is also great potential to address most of the issues relating to how to achieve effective and useful feedback. If the matter is approached adequately, the students should firstly have a choice whether or not to receive feedback. If they choose to receive feedback, it can be provided immediately and on demand through interactive communication between human users and computers, allowing it to be timely and multiple-try in nature. The feedback can also be tailored to individual needs and is thus highly personalized and task/process specific (cf. [20]).

Most software tools supporting the automated grading and assessment of CAD models, such as is currently provided to students in CAD courses at institutions of higher education, are limited by their metrics and by their assessment approach (cf. [2,4,5,7,9,14,16,17,35]). In particular, the metrics they use are of a rather static and exclusive nature, relying heavily on the final outcome. That is to say that they rely upon the completed CAD model, which then has its data structure compared to that of a fixed reference solution. Such approaches are not structured suitably to assess CAD model quality in regard to robustness and alterability due to their static and exclusive nature, which usually leads them to discount CAD model regeneration processes and their impact after alteration. They are also not sufficiently structured to explicitly support formative self-assessments carried out by students during individual steps of the modeling process as part of their exercise work. This problem arises because the software tools used are unable to assess partially created CAD models since they appear to be incomplete according to the metrics and rubrics provided in relation to the exercise specification and the fixed reference solution associated with it.

In general, it is quite challenging to specify sound modeling strategies that implement the correct feature-creation sequences and parameter settings that are required for robust parametric feature-based CAD models. Being able to design those sound modeling strategies is inherently difficult and represents a vast and complex problem space for creating robust CAD models. In order to make significant improvements, integrated solutions relating to the development of competency, skills, and software tools are required. However, the current state of development consists of rather isolated heuristics and approaches that can either reduce the problem space through methodology-based improvements to modeling strategies or help in detecting very limited sets of CAD model deficiencies after model creation has been finalized. Recent work in this direction, such as the resilient modeling strategy [10], the explicit reference modeling methodology [3], and the robust sketch principles [25], are promising approaches toward that goal. However, due to their limitations (see also discussions in [6]), translation of those approaches into practice is still impeded and not widely pursued. In general, research and development for achieving sound, flexible, and robust CAD models are still in their infancy, and thus unable to provide systematic approaches and methods that can actually prevent errors in associativity.

Another path to the issues outlined above is to aim at a dynamic approach to alterability analysis to enable timely and high-quality formative feedback that is provided by a software-based agent to support student-driven self-assessment. Here, instead of analyzing the status and quality of a finished CAD model in terms of static structures and elements, dynamic criteria computed through a knowledge-driven simulation-based analysis and assessment offer one quite effective solution. This was realized by the authors through development of a novel concept, namely dormant deficiency, and a metric that can be used to detect, characterize, and visualize defects that impact the robustness and alterability of CAD models. This novel concept and metric are not explicitly linked to flaws in static model structures and entities, but are related to errors in feature associativity, which have a non-static nature as they do not become activated and visible at the time of their introduction into a CAD model.

To address those shortcomings outlined above, while trying to translate the new approach into educational practice, among other issues, a software-based feedback agent has been developed, and this was introduced recently during the restructuring of a mechanical engineering CAD (MCAD) course. To translate the insight from lessons learned into improvements of and support for this feedback intervention, a two-step project follow-up was initiated, with results from the first step being reported in this paper.

2 BACKGROUND, SCOPE, AND OBJECTIVES

The project follow-up described in this paper is a spin-off project that expands upon previous work. That is, it represents continuing improvements to an MCAD course that was restructured lately. A selection of some major project milestones, with related results and outcomes achieved, is shown in Figure 1, together with those of the recently initiated project follow-up.

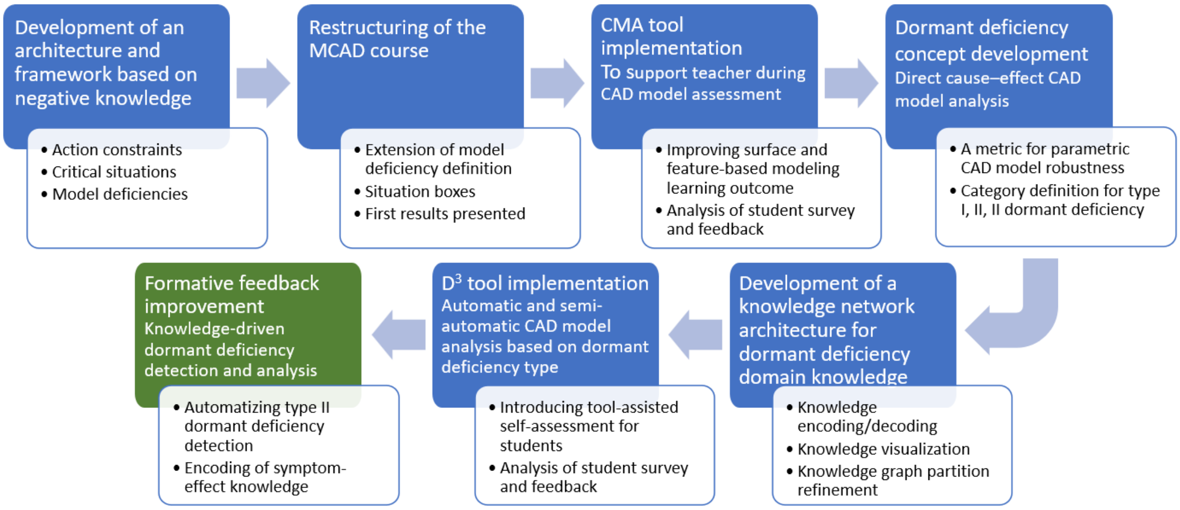


Figure 1: Overview of development stages of the restructuring of an MCAD course depicted through a selection of project milestones with related results and outcomes.

The restructuring of the MCAD course consisted of various types of improvement (cf. [21]), including the development of negative CAD domain knowledge and expertise and the development of the working knowledge and skills required to create robust alterable parametric CAD models. The latter was approached by introducing the dormant deficiency concept and metric. This concept includes three types of dormant deficiency (cf. [27]) and is aimed at supporting students in acquiring the knowledge and skills development needed to create robust alterable CAD models. To provide a means for students to see this concept coming alive, as well as having timely high-quality feedback on this metric applied to the CAD models that they have created in the CAD laboratory and in exercise assignments, a software-based feedback agent was developed, and subsequently provided to all MCAD course students. Analysis and evaluation of project outcomes, a survey, and engagement with students during lectures and exercises provided several precursors for improvements required and for the directions in which those might be pursued. One such indication was the need for improvement of the feedback – generated by the software-based feedback agent – related to type II dormant deficiencies.

Type II dormant deficiencies are part of a novel dormant deficiency concept and classification system, with a metric that describes and quantifies the impact that feature associativity errors can have on parametric feature-based CAD models (cf. [27]). Those errors in associativity, which were introduced during the modeling process due to mistakes in the specification of dependencies between geometric entities, remain dormant until an actual CAD model regeneration is triggered and executed through an alteration. As type II dormant deficiencies relate to faults in shape, the effect of this type of deficiency is that a regenerated CAD model does not contain any features labeled with a warning or failed status, but the shapes of features are incoherent or even destroyed completely. An example of this is where a cutout feature is partially moved outside the geometric boundary of the target body. The main symptom of a type II dormant deficiency that has been activated is a change in the local topology of the features affected by this deficiency.

The objective of the first part of this two-step project follow-up was to improve both the amount and the quality of the interaction with the feedback provided by the software-based agent in relation to type II dormant deficiencies. This, in turn, required the formalization and encoding of domain knowledge on type II dormant deficiency symptoms and effects and their relationships, upon which autonomous computation of information related to this type of deficiency can be based, in order to improve the provision of agent-based feedback.

3 APPROACH AND DEVELOPMENT

3.1 Outline

Development and implementation of feedback improvements in regard to type II dormant deficiencies, as outlined elsewhere in this paper, were carried out within several prominent project steps, as follows.

First, a systematic analysis of computed type II dormant deficiencies was conducted, which endeavor was supported by extensive empirical studies to gain a deeper insight into type II dormant deficiency symptoms. This was achieved by taking into account the nature of the dormant deficiency (cf. [27]) and carrying out structured analyses that focus on a change in the local topology of individual features affected by the type II dormant deficiency. The results were then used to compile symptom categories for type II dormant deficiencies in regard to individual feature types.

Second, a further round of empirical studies was conducted to aid a detailed analysis of the effects that type II dormant deficiencies have on individual features. This analysis of effects was based on the symptom categories that had been created in the previous step outlined above. The results of this second round of empirical studies were used to compile effect categories for type II dormant deficiencies in regard to individual feature types.

Third, the results from the previous two studies, in the form of symptom categories and effect categories for type II dormant deficiencies, were used to compile and formalize knowledge on symptom and effect relationships for this dormant deficiency type in regard to individual feature types.

Next, the formalized knowledge of symptom and effect relationships for type II dormant deficiencies, in regard to individual feature types, was encoded using a knowledge network based on attributed r-partite graphs (cf. [8,12,27]). In particular, graph partitions related to symptom categories and effect categories for type II dormant deficiencies were extended through newly created partition refinements.

Finally, the results of the previous steps, as outlined, were implemented as extensions of the software-based feedback agent. This feedback agent, in turn, is an integrated part of a larger computerized tool system for MCAD education that includes, among other components, a parametric CAD model alteration simulator and a visual simulation display (cf. [22,26]). Further extensions include added functionality that permits student users to enable and directly control – through the graphical user interface of the tool system – transparent CAD model shape rendering and selective feature shape coloring. This fully supports knowledge-driven detection and analysis of type II dormant deficiencies in regard to their symptom and effect relationships, and it is upon this foundation that extended formative feedback enriched in quality through visualization and offering more detailed information on those dormant deficiencies can be autonomously generated by the software-based feedback agent. Further details of the previous steps, as outlined, are discussed in the following sub-sections.

3.2 Determinants of Feedback Improvement

Considerable improvement in student performance and in learning outcomes was achieved with the previously introduced feedback-based educational intervention (cf. [22,23]). However, it also became evident that students still have difficulties when it comes to handling and correcting shortcomings and errors in their CAD models in regard to type II dormant deficiencies. This led to a focus, within this project follow-up, on extending and improving the quality, scope, and detail of the feedback generated by the software-based feedback agent. This included offering a better structured and more circumstantial information space on type II dormant deficiencies. It also included the provision of additional user interaction components on the dashboard of the feedback agent, and this should enable the improved feedback to provide to the students – among other facets and valuable information – a more delineated view on, and hopefully a better understanding of, type II deficiency and its impact on their CAD models.

Details and requirements for the design of the formative feedback extension, in regard to both information space and user interaction, were driven by several factors. First, there were some technological issues pertaining to data structure access and graphical user interface functionality of the commercially available parametric CAD system used, namely Solid Edge from Siemens Digital Industries Software (cf. [31]). Second, it was necessary to consider functional scope in regard to knowledge-driven fully automated type II dormant deficiency detection and subsequent analysis of symptom and effect relationships. Third, and most importantly, the needs of the MCAD course students were regarded as a priority. These were determined to a large extent from the results of a formative usability study of the software-tool based feedback agent, in addition to a student survey, and observations made through interactions with students during MCAD course lectures and CAD laboratory exercises (see also reports in [22,23]).

Formative feedback extensions in regard to the information space that is provided to the student user should include information on which features are affected by or involved in type II dormant deficiencies detected by the tool system, and where those features are located in the CAD model. This would help students to better locate the deficiency and subsequently navigate more systematically through their CAD models. However, to aid understanding, and to further an analysis into possible causes of those CAD model deficiencies, additional feedback, with more detail, is required. This should include information on the nature and range of parameter alteration, and individual point values of feature parameters, such as hole or pocket dimensions, which are related to the symptoms and the effects the type II dormant deficiencies produce on those features which are affected.

Extensions in regard to user interaction with the feedback agent should include means to support the graphical representation of symptoms, and effects on features affected by type II dormant deficiencies. This needs to be approached in regard to both the local changes in the topology/geometry of a feature, as well as its shape, and the interaction between features, in particular unintended feature intersections. In the case of local changes in a feature, these are sometimes very difficult to visually pinpoint and recognize. Typical situations that are challenging even for experts, let alone novices, include the identification and tracking down of sliver faces, minuscule gaps in a feature/model boundary, and local changes that occur within the interior of the CAD model, mostly due to unintended feature interactions. To aid students in analyzing and making sense of the unintended feature interactions that occur after parameter alteration and CAD model regeneration, explicit control of some visual attributes, such as hue, is necessary. This control needs to extend across entities in the set of affected features that is a part of the extended feedback information space, and across their counterparts in the linked CAD system. Particularly during the analysis of non-trivial feature intersections, this helps in visually identifying and keeping track of topological/geometrical entities, such as faces, and the features to which they belong. This explicit control of some visual attributes has to include not only those entities that are part of the design intent and original CAD model creation, but also those additional entities that are the result of type II dormant deficiencies. Note that checking for and simply removing those additional entities, such as sliver faces, from a CAD model, which can be done in many commercial CAD systems through basic user commands, is not the solution here because it neither prevents a dormant deficiency from being activated again nor removes its root cause. Moreover, such an approach is inadequate in an educational context, where the focus is on learning, understanding domain-specific concepts, and skills development rather than on delivering commercial solutions quickly and efficiently.

3.3 Elements and Keystones of Feedback Improvement

3.3.1 Knowledge compilation on type II dormant deficiency

Description of type II dormant deficiency

Dormant deficiencies can be conceptualized as errors in associativity which were introduced during the modeling process due to mistakes in the specification of dependencies between geometric entities and features. However, the effect and impact of those mistakes on the CAD model remain dormant until an actual CAD model regeneration is triggered and executed through an alteration (see also [22,27]). In this context, the outcome in regard to type II dormant deficiencies is related to an error situation, which, in turn, relates to features and their shape (topology/geometry). Hence, type II dormant deficiencies relate to faults in shape, as the effect of this type of deficiency is that a regenerated CAD model does not contain any features labeled with a warning or failed status that would also show up in the graphical user interface (GUI) of a CAD system. Nevertheless, in those cases, the shape of features is incoherent or even destroyed.

Symptoms and effects of type II dormant deficiency

In the case of type II dormant deficiencies, symptoms appear in the form of a change in the number of topological/geometrical entities of a feature, due to a change in the manner a feature shape intersects with other feature shapes. This change in the manner in which feature shapes intersect is, in turn, due to a change in the dimensions or positions of those features. Dimensions and positions of features depend on the reference plane where the feature profile is located, the extrusion options, and the way the profile has been dimensioned and constrained. Therefore, in general, individual symptoms regarding a change in the number of topological/geometrical entities of a feature can be associated with specific cause and effect relationships, and this facilitates analysis and backtracking to causal factors and eventually to the root cause of the type II dormant deficiency.

In the following an overview is given on how results and insight from empirical work on local changes in topology of features that were caused by a type II dormant deficiency were used to compile and encode domain-specific knowledge. This domain-specific knowledge, in turn, represents a base for the knowledge-driven autonomous analysis of related symptoms and effects. To keep matters transparent and implementation-independent, collections of structured data objects, using a set-based notation, are used to outline the formation of categories for type II dormant deficiency symptoms and effects. These, in turn, were implemented through refining partitions of attributed r-partite graphs within the framework of a knowledge network, as described in [27]. In a nutshell, within this context, by and large those categories are realized through graphs in which paths can be composed.

Symptoms, in the form of local changes in the topology of features that were caused by a type II dormant deficiency are characterized by the location and the type of such changes as expressed in Equation 1.

$$symptom^{II} = change\_location \times change\_type \quad (1)$$

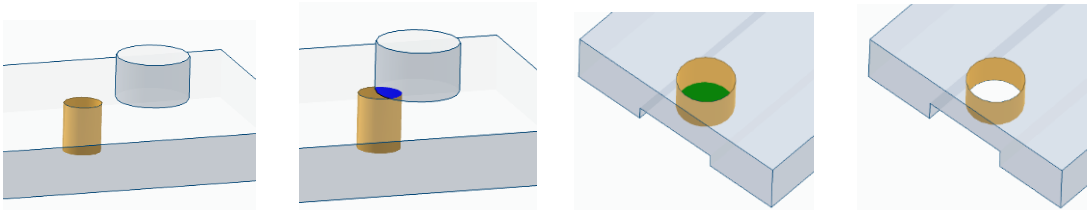
Those changes in the topology of features usually occur in the bases (top/bottom) and the sides of features as formulated in Equation 2. The type of such changes in local feature topology is related

$$change\_location = \{feature\_base, feature\_lateral\} \quad (2)$$

to the type of topological entities that are being added and/or removed (see Equations 3-5) as is

$$change\_face = \{add\_face, remove\_face\} \quad (3)$$
$$change\_loop = \{add\_loop, remove\_loop\} \quad (4)$$
$$change\_edge = \{add\_edge, remove\_edge\} \quad (5)$$

expressed through the disjoint union in Equation 9. At this point, perhaps, some examples are in order to illustrate the nature of the equations introduced, after which the mathematical description of type II dormant deficiency symptoms and effects can be resumed. In the following examples the visual appearance and impact on feature shapes is described, both before and after feature intersection, in respect to local changes in topology in terms of topological entities. To keep the examples transparent, only basic volume adding and volume removing features, with a non-complex topology and shape, are used.

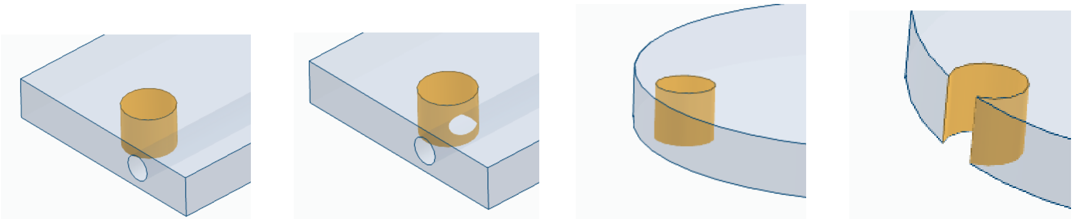


(a) (b) (c) (d)

Figure 2: Changes in the local feature topology in regard to the set of faces: (a) initial CAD model state with a through hole, (b) regenerated CAD model with a through hole and its modified topology, (c) initial CAD model state with a blind hole, (d) regenerated CAD model with a blind hole with bottom face removed.

Figure 2 shows typical examples of a topological change of intersecting features that takes place in the set of faces after an altered CAD model is regenerated. In Figure 2(a), the initial CAD model state is shown with a through hole comprised of 1 lateral face. After the alteration of a critical parameter and regeneration of the CAD model, an unintended feature intersection occurs as a result of an activated type II dormant deficiency that was introduced due to an error in feature associativity. This leads to a change in the topology of the through hole. In this example, a base face is added to the top of the through hole, as shown in Figure 2(b). In a similar scenario, however, involving a blind hole afflicted with a type II dormant deficiency, as shown in Figure 2(c), the regeneration of the CAD model results in a change in the topology of the blind hole so that its base face at the bottom is removed (see Figure 2(d)).

Figure 3 shows typical examples of a topological change of intersecting features that takes place in the set of loops after an altered CAD model is regenerated. In Figure 3(a), the initial CAD model state is shown with a through hole comprised of 1 lateral face, which in turn is bound by two loops. After the alteration of a critical parameter and regeneration of the CAD model, an unintended feature intersection occurs as a result of an activated type II dormant deficiency, as shown in Figure 3(b). This leads to a change in the topology of the through hole, which, however, is different from that in the previous case.



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

Figure 3: Changes in the local feature topology in regard to the set of loops: (a) initial CAD model state with a through hole, (b) regenerated CAD model with an unintended feature intersection involving the through hole, (c) initial CAD model state with a through hole, (d) regenerated CAD model with the through hole and modified topology.

The unintended intersection of this through-hole feature with a volume-removing feature within the CAD model interior results in the creation of another lateral loop on the side of the through-hole feature. A typical example where a loop is removed – after alteration of a critical parameter and regeneration of the CAD model – from the set of 2 loops forming the boundary of the cylindrical face is shown in Figure 3(c) and Figure 3(d).

(a) (b)

Figure 4: Changes in the local feature topology in regard to the set of edges: (a) initial CAD model state with a cylindrical extruded protrusion feature, (b) regenerated CAD model with a cylindrical extruded protrusion feature and modified topology.

Figure 4 shows typical examples of a topological change of intersecting features that takes place in the set of edges after an altered CAD model is regenerated. In Figure 4(a) the initial CAD model state is shown with a loop on the lateral face of a cylindrical extruded protrusion feature formed by just one edge. After the alteration of a critical parameter and regeneration of the CAD model, an unintended change in feature intersection occurs as a result of an activated type II dormant deficiency, as shown in Figure 4(b). This leads to a change in the topology of the cylindrical extruded protrusion feature; that is, one edge is added to the loop on the lateral face. Now, the loop is formed by two edges (see again Figure 4(b)). Reversing this scenario by considering an initial CAD model state as shown in Figure 4(b), alteration of a critical parameter and regeneration of the CAD model with a result as shown in Figure 4(a) would represent an example of a change in the topology of the cylindrical extruded feature where one edge is removed from the loop on the lateral face. Note that reversing the order of the initial CAD model state, parameter alteration, and model regeneration in the scenarios shown in Figure 2 and Figure 3 can also serve as an example for topologic entities such as faces and loops being removed from a local feature topology.

$$change\_face\_type = \{x \mid x \in (change\_face \cup change\_loop \cup change\_edge)\} \quad (6)$$
$$change\_loop\_type = \{x \mid x \in (change\_loop \cup change\_edge)\} \quad (7)$$

$$change\_edge\_type = \{ x \mid x \in change\_edge \} \quad (8)$$

Note that changes involving only edges are the most specific type of change in local topology, excluding any change in sets of both loops and faces (cf. Equation 8). Changes in local topology involving loops may also include changes in sets of edges, but exclude changes in sets of faces (cf. Equation 7). Changes involving faces are the most general type of change in the local topology of features (cf. Equation 6).

$$change\_type = change\_face\_type \sqcup change\_loop\_type \sqcup change\_edge\_type \quad (9)$$

Individual effects related to symptoms (see again Equation 1) need to be classified according to the location where changes in the topology of features occur and the type of topological entities involved. In a similar manner as approached in Equations 6-8, taking into account faces, loops, and edges at the bases of features (see Equations 10-12) the related effects can be defined as shown in Equation 13.

effect_base_face = {"feature covers an entrance", …,
…, "feature moves out of the model boundary", …} (10)
effect_base_loop = {"feature is included in a base face",
…, "feature is removed from a base face", …} (11)
effect_base_edge = {"feature splits edges of a base loop", …,
…, "feature merges edges of a base loop", …} (12)

$$effect\_base = effect\_\ base\_face \sqcup effect\_base\_loop \sqcup effect\_base\_edge \quad (13)$$

Analogous to the situation in Equations 10-12, effects related to faces, loops, and edges at the sides of features (see Equations 14-16) can be defined as shown in Equation 17.

effect_lateral_face = {"feature is split into two or more parts", …,
…, "feature merges lateral faces", …} (14)
effect_lateral_loop = {"feature is included in a lateral face", …,
…, "feature is removed from a lateral face", …} (15)
effect_lateral_edge = {"feature splits edges of a lateral loop", …,
…, "feature merges edges of a lateral loop", …} (16)

$$effect\_lateral = effect\_lateral\_face \sqcup effect\_lateral\_loop \sqcup effect\_lateral\_edge \quad (17)$$

Now, based on Equation 13 and Equation 17, the effects of type II dormant deficiency can be defined as shown in Equation 18. Note that the types of change in local topology as defined above are not always applicable to all feature types. For example, in the case of through hole features, base faces can be added, resulting in features that are covering entrances, and these are recognized as symptoms. However, in general, the symptom of base faces being removed is not applicable in the case of through hole features. To provide co-domain elements in Equation 22 for those cases, Equation 18 includes a disjoint union element additional to those defined in Equation 13 and Equation 17.

$$effect^{II} = effect\_base \sqcup effect\_lateral \sqcup effect\_void \quad (18)$$

As symptom and effect relationships are specific to each feature type in respect to a CAD system, Equations 19-21 need to be taken into account to define a map with a domain of feature types and symptoms and a co-domain of effects as shown in Equation 22.

$$cad\_system = \{solid\_edge, \ldots\} \quad (19)$$
$$feature\_set = hole\_feature \cup extruded\_protrusion\_feature \cup \ldots \quad (20)$$

$$feature\_type = cad\_system \times feature\_set \tag{21}$$
$$feature\_type \times symptom^{II} \rightarrow effect^{II} \tag{22}$$

Also note that the map in Equation 22 encapsulates knowledge on what is accomplished. That is, it tells – within the context of type II dormant deficiency – which symptoms for individual features and their type result in what kind of effect. In some of the previously introduced equations, the disjoint union of families of sets is used to retain the origin of set elements while providing transparency for building co-products of the category of sets and the resulting partition refinements for newly added portions of *r*-partite graphs. Those, in turn, are integrated with a knowledge network on cause and effect relationships in regard to dormant deficiencies (for more details on this knowledge network and partition refinements specified, see [27]). The main components of the software-based feedback agent are implemented in Visual Basic for Applications (VBA). Interface structures of the feedback agent, such as the dashboard, are implemented within Microsoft *Excel* using VBA functions and procedures. Those, in turn, are further integrated with software modules containing an alteration process simulator and analysis/assessment algorithms (cf. [22]). As the CAD modeling environment – which deploys a commercially available parametric feature-based CAD system, namely *Solid Edge* from Siemens Digital Industries Software – and the simulation-based analysis/assessment environment are cross-linked, the feedback agent can indeed provide in real time a visualization of the symptoms and effects that dormant deficiencies can have on the altered CAD models which are being regenerated. However, at this point, more technical and implementation-specific details are beyond the scope of this paper.

Linear and non-linear type II dormant deficiency

The type II dormant deficiencies discussed above can be distinguished according to their relationship with critical parameters that cause such deficiencies through the introduction of errors in feature associativity. A type II dormant deficiency that becomes active immediately after CAD model regeneration and increases proportionally to the value change in the parameter that is causing such a deficiency is referred to as a linear type II dormant deficiency. Such a deficiency usually occurs when elements involved in the definition of feature geometry and feature positioning within a CAD model are explicitly constrained using driving dimensions instead of formula-based constraints. Common examples frequently encountered in student-created CAD models include the explicit use of fixed positioning dimensions as the sole constraint for the location of circular profiles.

A type II dormant deficiency that does not necessarily become active immediately and does not increase proportionally to the value change in the parameter that is causing such a deficiency is referred to as a non-linear type II dormant deficiency. Such a deficiency usually occurs when incorrect reference elements are used during the constraint of profiles. Typical examples often found in student-created CAD models include the explicit use of individual topological/geometrical entities, such as edges and points, to constrain a circular profile and its spatial location within the CAD model. Those topological entities are incorrectly used as a kind of direct reference instead of an actual geometric constraint between such entities. Although those attempts might work for certain CAD model configurations – and evidently many students have managed to create CAD models using such erroneous and highly unstable constraint definitions – such CAD models usually become deficient after parameter alteration and model regeneration. This is due to local changes in topology and geometry, which, in turn, cause topological/geometrical entities to be altered, too, or even removed, and that may include those entities explicitly used in the erroneous constraints.

3.3.2 Enhanced information space and user interaction with the feedback agent

The extended and improved information space of the feedback is now provided through list-based information in the dashboard and several additional tabs, as shown in Figure 5. The visual representation of type II dormant deficiency-related symptoms and effects is supported by selective feature shape coloring, transparent CAD model shape rendering, and brushing (see upper and lower Figure 5). This (cf. [24,32]) allows users to directly visualize and access affected features and their parameters in the CAD model (see again lower Figure 5) through interactive means such as pointing at and clicking on entities within list-based information from the feedback provided. Also provided within the improved information space through the dashboard of the feedback agent is detailed information on individual features where type II dormant deficiencies could be detected by the system, such as feature type, feature identifier, features affected by the deficiency, and the critical parameter/dimension linked to the type II dormant deficiency. Information on the last is comprised of an identifier, the value range, and individual point values. In the following an overview is given on user interaction components with the feedback agent and improvements made in regard to the extended feedback information space.

To outline how the feedback improvements presented in this paper are being integrated and used from a student user perspective, a selection from a concrete user interaction session with the current feedback agent – that was made available to all MCAD course students enrolled this academic year – is presented in the following. First, the CAD model subject to analysis needs to be connected to the feedback agent and the tool system by clicking the "Link to CAD Model" button (see (1) in Figure 5). This can be done at any time while working on a CAD model. To maximize the benefit for support and learning this feedback agent offers, it is recommended that it be used as early as possible during CAD modeling exercise work, thus linking CAD models to the feedback agent while they are in the early stages of creation. Second, to initiate and run an analysis of the linked CAD model, the "Run Test" button (see (2) in Figure 5) is clicked. Major results of the robustness analysis are reported in the main table along with the feature identifiers and types, and altered CAD model parameters such as dimensions with their respective point values. Note that the range of these values can be controlled by the user through a setting on the "Dimension Alteration Factor" (see (3) in Figure 5). Each row of the main table, and the information reported in that row, is associated with a dimension that has been altered to assess the regenerated CAD model. If the change of a dimension results in a type II dormant deficiency being detected in the CAD model, the background of the respective data entry in the feature type column will be colored in magenta red (see (4) in Figure 5).

Next, by selecting the corresponding data entry in the "Dimension" column (see (5) in Figure 5) and by clicking on the "Change" button (see (6) in Figure 5), the user will change the background color of this data entry from white to orange-yellow (see again (5) in Figure 5) and the corresponding dimension and its impact will be tested and analyzed by the system. Note that all point values during the simulated alteration are both reported in the right-hand side of the main table and also explicitly shown and highlighted in orange in the CAD system interface along with each regenerated CAD model shape (see lower part in Figure 5). Note that the features affected by the altered dimension – in terms of a change in the number of edges, loops, and faces – are listed in the "Affected Features" column (see (7) in Figure 5). The affected features highlighted in the CAD system interface can be selected in the feature list (see (8) in Figure 5) and set for selective feature shape coloring with the "Add Color" button (see (9) in Figure 5). The parameter alteration and CAD model regeneration process can then be run again by clicking on the "Change" button (see again (6) in Figure 5) to resume and deepen the analysis of the impact of the parameter alteration with a focus on the highlighted features affected by the deficiency.

The lower left in Figure 5 shows the CAD system interface that accompanies the various user interaction steps outlined above. It shows the CAD model shape rendered in transparent mode, and the dimension subject to analysis is highlighted in orange. The various faces of the feature investigated are shown with a colored appearance due to the use of selective feature shape coloring (see again (8) and (9) in Figure 5). The central figure shows the model with an increased value for the dimension being tested and the resulting model topology/geometry with its shape after regeneration. Note that additional faces (colored in purple-blue) have been added to the feature under investigation, and these have appeared as a symptom of the type II dormant deficiency that was detected earlier by the tool system and documented in the agent-generated feedback. The lower right of Figure 5 shows a similar scenario but with a decreased value for the dimension being tested. In this case, no changes in local feature topological/geometry can be detected with respect to the original variant of the CAD model.

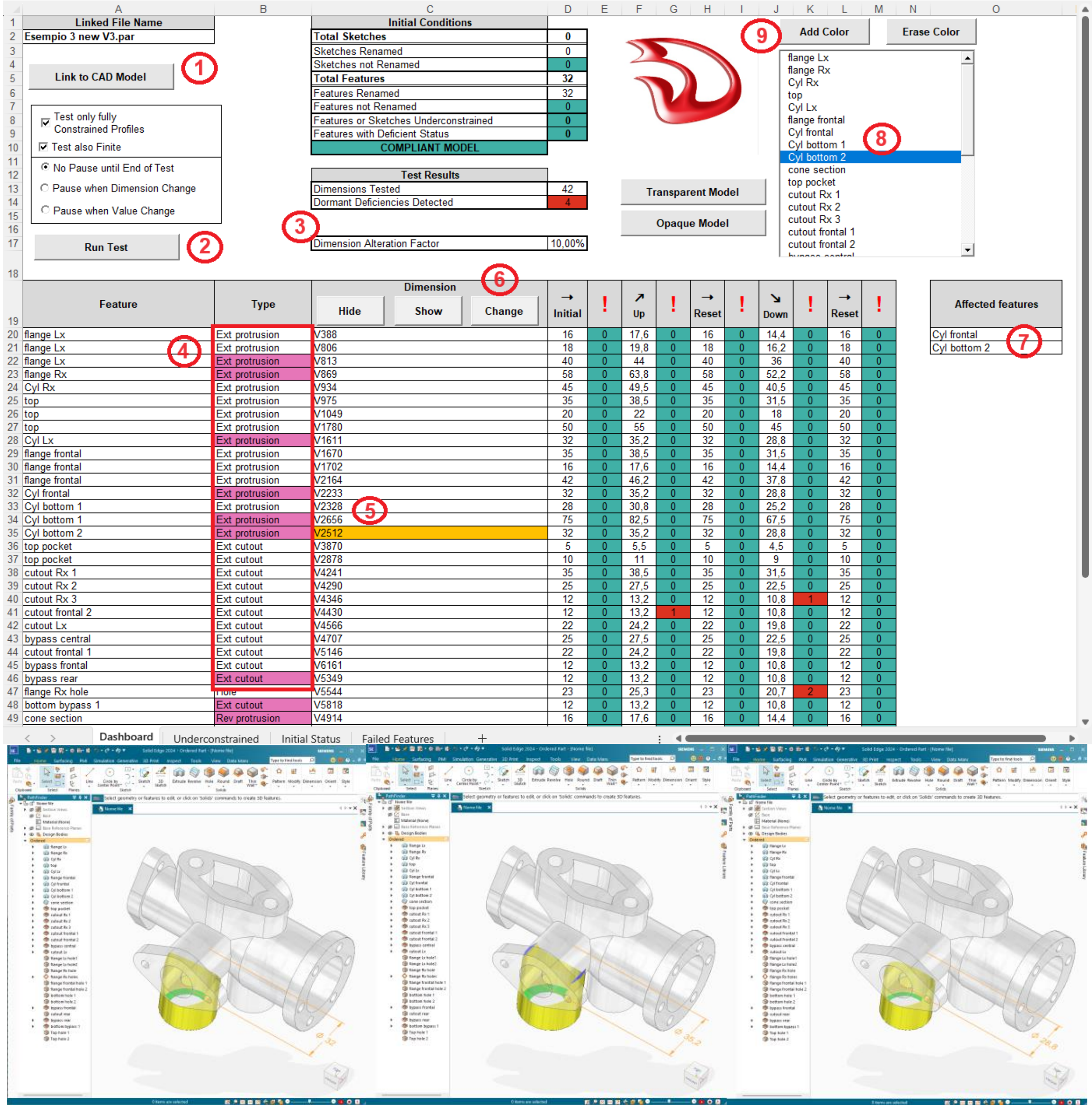


Figure 5: Example of the user interface and agent-based feedback that are cross-linked to the CAD system and its graphical user interface. The latter is displaying contents with selective feature shape coloring activated and the CAD model rendered in non-opaque mode.

In Figure 6, the same CAD system interface scenarios and contents are shown, as depicted earlier, in the lower part of Figure 5. However, here, the CAD model is rendered in its usual non-opaque mode, and it becomes obvious that such a mode has some disadvantages when it comes to visually recognizing and tracking type II dormant deficiency symptoms and effects. Note that, due to the visual simulation display concept and brushes used in the implementation (cf. [22,24,32]), the user interface windows of the feedback agent and the CAD system can be freely arranged in size and position on a single computer display or on multiple physical display devices using a computer with several external monitors connected to it.

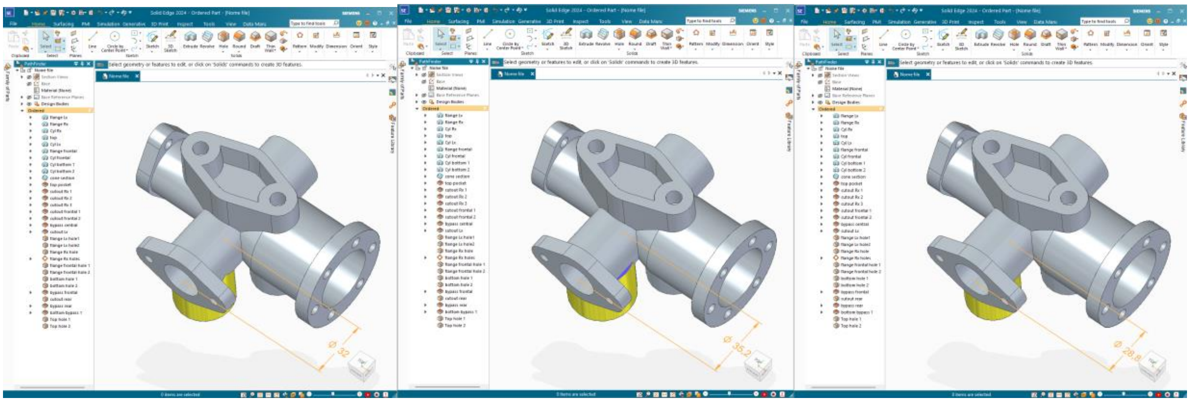


Figure 6: Example of the CAD system interface displaying contents with the selective feature shape coloring activated and the CAD model rendered in the usual opaque mode.

4 EXAMPLES FROM EDUCATIONAL PRACTICE

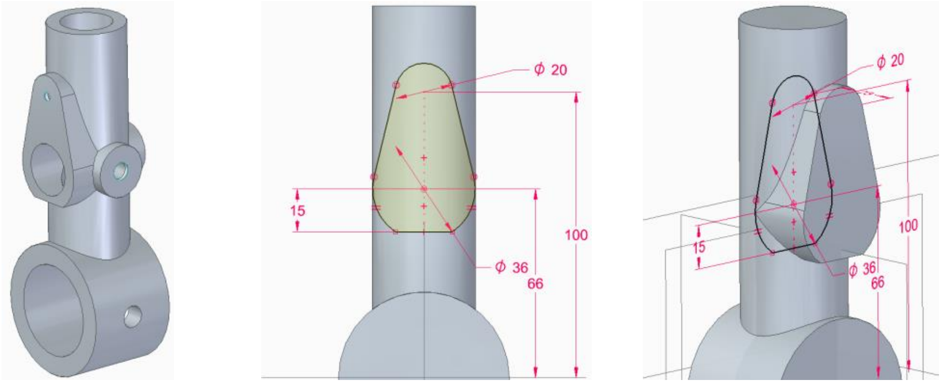
4.1 Overview

Results of manual analysis conducted by the authors – initially of 75 student-created CAD models – combined with theoretical work (cf. [23,26,27]) were used as a base to elicit and compile knowledge on type II dormant deficiency regarding symptoms and effects. This knowledge base was then encoded and implemented, along with improvements to the feedback agent, and increasingly employed during continued empirical research to enlarge and verify the knowledge compilation on type II dormant deficiency regarding symptoms and effects. This gradually led to documented inspection and analysis of over 250 student-created CAD models, and this was used to facilitate knowledge elicitation and compilation specifically on type II dormant deficiency. In the following sub-sections, annotated examples from empirical work on type II dormant deficiency analysis for both linear and non-linear effects are presented.

4.2 Type II Dormant Deficiency and Linear Effects

In this sub-section, examples of type II dormant deficiency with a linear effect are presented and discussed. These examples were encountered during CAD model analysis and interaction with the feedback agent. Recall that in such cases the deficiency and its effect usually appear in a direct and straightforward manner. They are usually proportional to the changes in certain critical parameters that are causing the deficiency in the CAD model configuration – through errors in feature associativity as the root cause. They appear from a dormant state during CAD model regeneration every time a critical parameter linked to the root cause of the deficiency is modified.

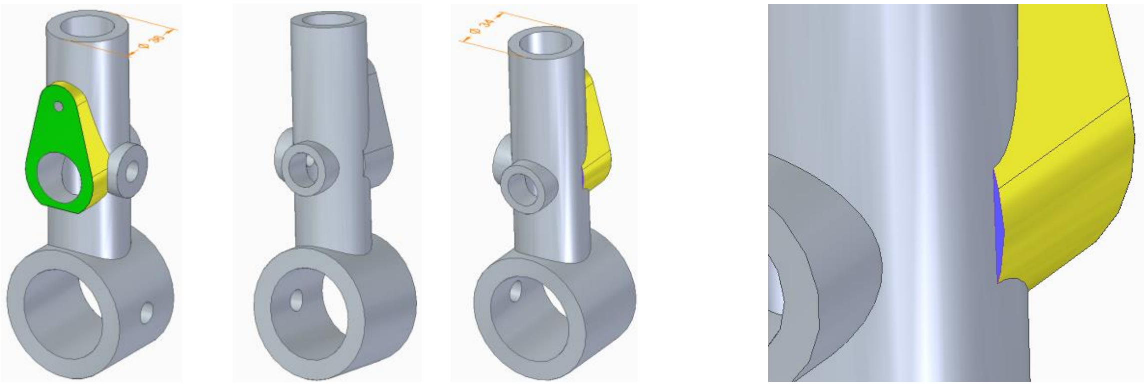
The example is a CAD model from an actual CAD course assignment. As depicted in Figure 7(a), the frontal boss is created with an extruded protrusion feature. The profile plane of this feature (see Figure 7(b)) is coincident with the XZ plane of the modeling space of the CAD system. However, the profile definition of this feature does not contain any constraint that will keep its profile tangential to the silhouette edges of the vertical base cylinder (see Figure 7(c)). This omission reflects a severe shortcoming in the modeling strategy employed by the student who created this feature.



(a) (b) (c)

Figure 7: An example of a CAD model from an actual CAD course assignment with a profile definition of its frontal boss, which leads to a type II dormant deficiency with a linear effect. From left to right: (a) rendered shape of the CAD model with unaltered parameter settings, (b) profile definition of the frontal boss, (c) profile definition and rendered shape of the frontal boss.

In fact, it introduces an error in inter-feature associativity (cf. [27]), which subsequently results in the introduction of a type II dormant deficiency into the CAD model. The symptom and effect, and thus the full impact of this deficiency, become immediately apparent during CAD model regeneration in cases where the diameter of the vertical base cylinder is reduced. In those cases, a very small step in the form of a tiny surface will be generated between the frontal boss and the vertical base cylinder (see Figure 8(b) and Figure 8(c)).

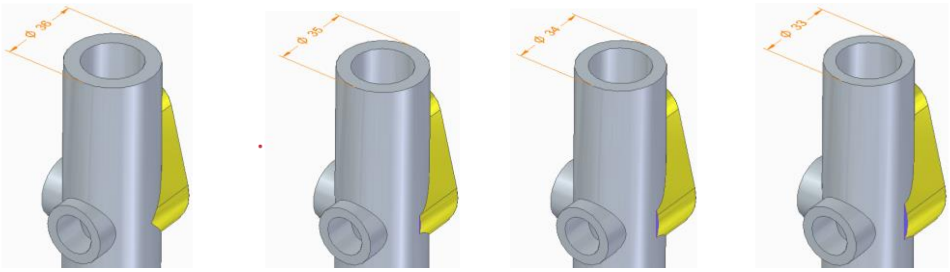


(a) (b) (c) (d)

Figure 8: Example of a CAD model from an actual CAD course assignment containing a type II dormant deficiency with a linear effect before and after the alteration of a critical dimension, using selective feature shape coloring. From left to right: (a) initial state of the CAD model without any alteration, (b) state of the regenerated CAD model with a critical parameter altered, (c) regenerated CAD model with the impact of the deficiency visually highlighted through selective feature shape coloring, (d) enlarged section of the regenerated CAD model where the impact of the deficiency takes place.

As can be seen in the example depicted in Figure 8(b), the effect and impact of the type II dormant deficiency are actually quite difficult to recognize visually due to their size. However, using the feedback agent and the newly added functionality such as selective feature shape coloring and display of the critical dimension and its history of value changes, as shown in Figure 8(c), Figure 8(d), and Figure 5, support can be provided to students in detecting, locating, and subsequently analyzing further any such dormant deficiencies. In this example, detection and analysis of the CAD model deficiency were based on knowledge about the feature type that was affected, the type and location of the symptom detected, and the nature of the effect derived. As mentioned above, a face has been added to the base of the extruded protrusion feature that was used to model the frontal boss, causing this feature, and thus the frontal boss, to move out of the original CAD model boundary as they become larger than the vertical base cylinder.

As the case shown in Figure 8 represents an example of a type II dormant deficiency with a linear effect, gradually changing the value of the critical parameter/dimension (see Figure 9(a)) that was found to be associated with this deficiency results in a simultaneous but gradual change in the symptom, as can be seen in Figure 9(b), Figure 9(c), and Figure 9(d). It also shows that the largest parameter value change causes the largest symptom (see Figure 9(d)) to appear, while smaller parameter value changes result in smaller symptoms (see Figure 9(b) and Figure 9(c)).

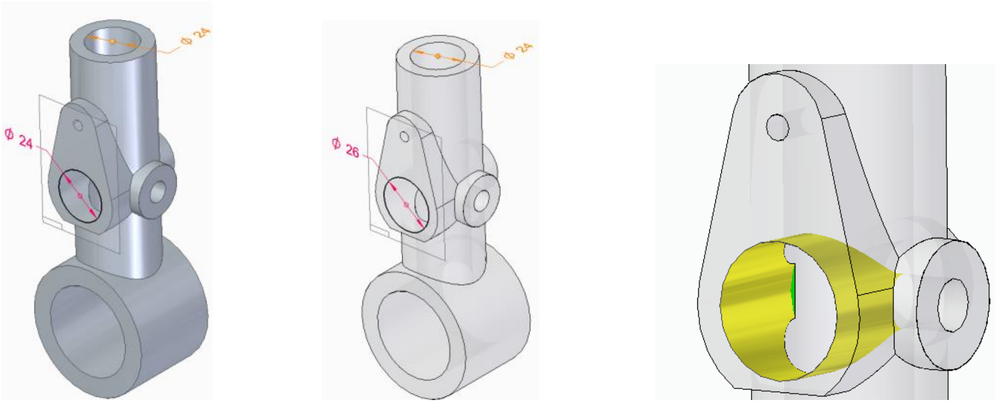


(a) (b) (c) (d)

Figure 9: Section of a CAD model from an actual CAD course assignment. The model contains a type II dormant deficiency with a linear effect and is shown before and after the alteration of a critical dimension using selective feature shape coloring. From left to right: (a) initial state of the CAD model without any alteration, (b) state of the regenerated CAD model with the critical parameter value reduced by 2.78%, (c) state of the regenerated CAD model with the critical parameter value reduced by 5.56%, (d) state of the regenerated CAD model with the critical parameter value reduced by 8.34%.

In cases where the effect and impact of a type II dormant deficiency are not only very small, but occurring within the interior of a CAD model, their detection by visual inspection alone through the standard GUI of a CAD system is impossible most of the time. Remember that commercial CAD systems are unable to detect or rectify any type II dormant deficiency. They are difficult to notice even for experienced users, let alone for novices and students.

Figure 10 provides a concrete example. It is another CAD model taken from the same CAD course assignment but created by a different student. This CAD model also contains a type II dormant deficiency with a linear effect similar to that shown in Figure 8. However, this time, the symptoms and effects of this deficiency are located within the CAD model interior (see Figure 10(b) and Figure 10(c)). Here, the feature used to model the frontal boss hole contains a profile that is not properly constrained so as to align in a manner tangential to the silhouette edges of the central inner hole of the vertical base cylinder. The circular extruded cutout feature used to model the frontal boss hole is extruding from the model interior up to the XY plane of the modeling space of the CAD system, as shown in Figure 10(a).



(a) (b) (c)

Figure 10: Example of a CAD model from an actual CAD course assignment. The model contains a type II dormant deficiency with a linear effect occurring within the model interior. From left to right: (a) initial state of the CAD model without any alteration, (b) state of the regenerated CAD model with a critical parameter altered, (c) enlarged section of the regenerated CAD model where the impact of the deficiency takes place, using transparent shape rendering and selective feature shape coloring.

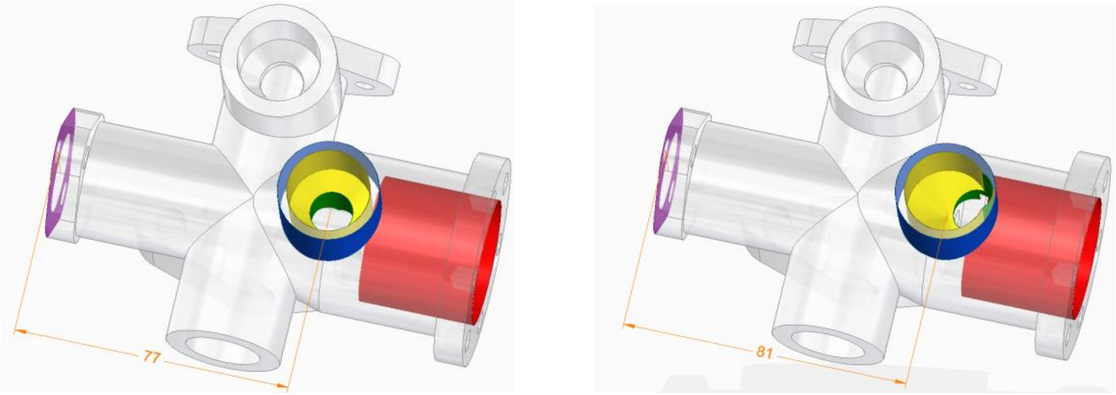
In cases where the diameter of the frontal boss hole is altered and exceeds the diameter of the central inner hole of the vertical base cylinder, a minuscule step in the form of a tiny surface is created at the bottom of this frontal boss hole (see Figure 10(c)).

4.3 Type II Dormant Deficiency and Non-Linear Effects

In this sub-section, examples of type II dormant deficiency with a non-linear effect encountered during CAD model analysis and interaction with the feedback agent are presented and discussed. Recall that in such cases, the deficiency and its effect only appear in certain parameter configurations of a CAD model. That is, they do not awaken from a dormant state during CAD model regeneration until the change of a critical parameter, such as a dimension, exceeds a certain threshold. In the example – also an example of a CAD model from an actual CAD course assignment – depicted in Figure 11(a), the effect and impact of the type II dormant deficiency detected become visible during CAD model regeneration in cases where the distance between the planar face (magenta top base surface) of the left flange and the circular boss (blue circular extrusion) reaches or exceeds 81mm (see Figure 11(b)).

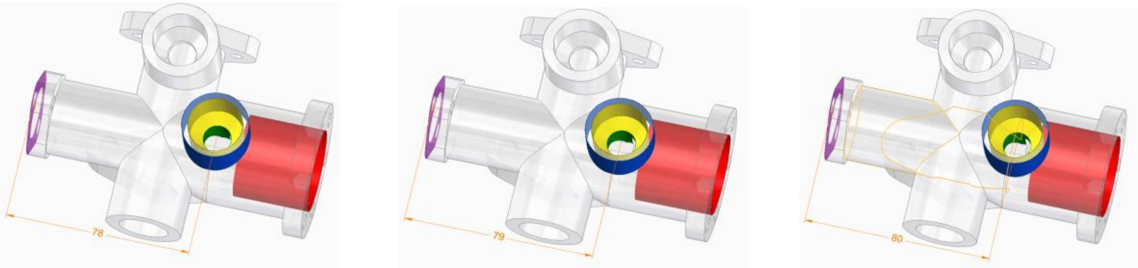
However, the effect and impact of the deficiency are invisible during CAD model regeneration while alterations to this critical distance parameter remain between its original value, which was set at 77mm (see again Figure 11(a)), and the value of 81mm (see Figure 12), at which point it becomes visible.

The faulty modeling strategy of this CAD model created an associativity error due to the incorrect constraint of profile elements between features, thus introducing this dormant deficiency into the model. The error occurred as follows. A circular boss (blue circular extrusion feature) was positioned at a certain distance from the planar face of the left flange (magenta top surface). Next, a hole with a conical end (yellow hole feature) was positioned with respect to this boss in a coaxial manner. Then, a through hole (green circular extruded cutout feature) was positioned in the center of this larger hole, as shown in Figure 11(a). Within such a configuration, an increase in the value of the dimension that determines the position of this circular boss results in the relocation of both the boss and its two inner holes toward the right side within the CAD model, as shown in Figure 13(a) and Figure 13(b).



(a) (b)

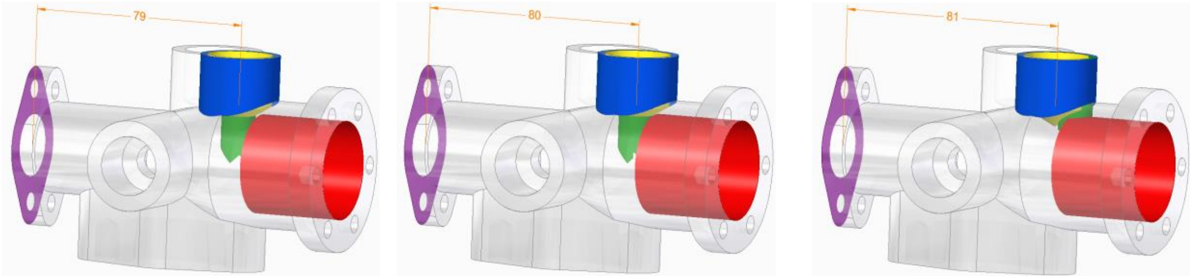
Figure 11: Example of a CAD model from an actual CAD course assignment. The model contains a type II dormant deficiency with a non-linear effect. This was encountered during CAD model analysis using selective feature shape coloring. From left to right: (a) state of the CAD model without any visible deficiency before alteration of the critical dimension, (b) actual state of the regenerated CAD model containing visible deficiencies after alterations to the critical dimension reach a threshold.



(a) (b) (c)

Figure 12: Example of a CAD model from an actual CAD course assignment. The model contains a type II dormant deficiency with a non-linear effect without any visible deficiency after alteration of the critical dimension, using selective feature shape coloring. From left to right: (a) state of the regenerated CAD model with the critical distance parameter set at 78mm, (b) state of the regenerated CAD model with the critical distance parameter set at 79mm, (c) state of the regenerated CAD model with the critical distance parameter set at 80mm.

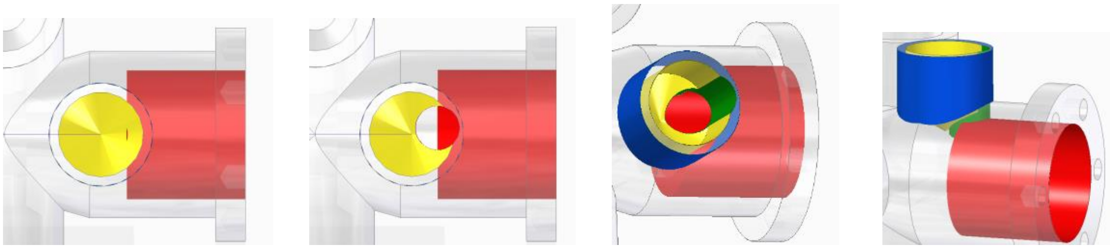
However, when this distance-defining dimension exceeds a certain value, the through hole does not remain in its intended position (see Figure 14(b)). The reason for this is that the center of the through-hole profile has been constrained to the apex (tip vertex) of the conical end of the yellow hole feature. When the circular boss (blue circular extruded protrusion feature) is moved to the right due to a value increase in the distance-defining dimension, at a certain point, CAD model regeneration results in the hole with a conical end (yellow hole feature) having a topology that is different from its original one (see Figure 14(a) and Figure 14(b)), this is due to the different intersection conditions between the yellow hole feature and the larger transversal hole (red horizontal circular extruded cutout feature), as shown in Figure 13(c) and Figure 13(d).



(a) (b) (c)

Figure 13: Side views of the regenerated CAD model containing a type II dormant deficiency with a non-linear effect after the alteration of the critical dimension. From left to right: (a) state of the regenerated CAD model with the critical distance parameter set at 79mm, without any visible deficiency, (b) state of the regenerated CAD model with the critical distance parameter set at 80mm, without any visible deficiency, (c) state of the regenerated CAD model with the critical distance parameter set at 81mm, at which point the deficiency becomes visible.

In this CAD model configuration, the vertex of the cone tip (apex) is no longer recognized by the CAD system as the constraint point of the center of the profile related to the through hole (green circular extruded cutout feature). In this CAD model configuration, unfortunately, the point becomes re-constrained – automatically through the CAD system during the CAD model regeneration – to another vertex that has appeared on the conical surface (see again Figure 14(a)).



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

Figure 14: Various views of the regenerated CAD model containing a type II dormant deficiency with a non-linear effect after the alteration (parameter set at 81mm) of the critical dimension. From left to right: (a) top view of unintended feature intersection, (b) top view of changed local topology after unintended feature intersection, (c) top view of unintended feature intersection and its effect on local topology and features affected after CAD model regeneration, (d) side view of unintended feature intersection and its effect on local topology and features affected after CAD model regeneration.

This local topology/geometry and its shape created during model regeneration obviously do not violate any of the rules used by the CAD system for defining features and assessing proper manifold solid models. Therefore, the deficiencies remain undetected by the CAD system, as do all type II dormant deficiencies, and their symptoms and effects. Note that in this case it would have been more effective to constrain the profile of the through hole (green circular extruded cutout feature) so that it was concentric with the hole with a conical end (yellow hole feature), instead of constraining the center of the circular profile. Not only would that have maintained the original design intent, but it would also have avoided the introduction of the type II dormant deficiency. In this example, detection and analysis of the CAD model deficiency were based on knowledge of the feature type affected, the type and location of the symptom detected, and the nature of the effect derived. That is, according to the discussion above, a lateral face has been added to the side of a through hole that was modeled with a circular extruded cutout feature, resulting in this feature being split into two or more parts as the shape of this through hole does not retain its original cylindrical surface.

5 CONCLUSIONS AND FUTURE WORK

Within the work presented, the approach, structures, and framework used for the formulation and encoding of domain knowledge on type II dormant deficiencies, and their symptom and effect relationships, have been outlined and discussed. This encoded domain knowledge has been integrated into a knowledge network that is linked to a software tool-based formative feedback agent, which was provided to students in a recently reformed MCAD course. This extension of the agent-based formative feedback was driven by tangible evidence of previous project outcomes and is aimed at improving learning experiences and skills development during CAD laboratory exercises and course assignments, particularly supporting the self-assessment and self-adjustment efforts of students while practicing the design and creation of robust, alterable parametric feature-based CAD models.

The second step of this project follow-up is planned for this and the next academic year. It includes releasing the improved and extended software tool-based formative feedback agent and monitoring the efficacy and progress of this educational intervention. Work pertaining to this will seek to determine and verify qualitatively and quantitatively the impact of the improved educational intervention for MCAD. This will be approached through a multi-method analysis and assessment including, among other components, an analysis of a student survey and effect size calculations regarding the software agent-based feedback intervention and its improvements. Furthermore, a detailed analysis/assessment of the quality of CAD models created by students and submitted during CAD laboratory and exercise assignments will be included. Depending on the outcome, further project follow-ups and spin-off projects will be considered in regard to student engagement, continuous improvement, and sustainability.

The aim is to provide opportunities to engage with students in order to learn more about their concerns and needs. It is necessary to identify areas for improvement in a manner that allows for adjustment and refinement so as to ensure that, in the long run, this educational intervention will be able to sustain its quality and provide substantial benefits while still retaining effectiveness and efficiency.

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