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Critical Thinking in a Solid Modeling Course

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Abstract

Computer aided design software (CAD) is used in the engineering field to create parametric solid models (models). The models describe the size, shape and feature content of an object and can be used for a variety of analyses including but not limited to dimensional, structural, and thermal among others. If the model dimensions and features behave parametrically and the model incorporates design intent, a great number of scenarios can be efficiently explored by manipulating the model using onboard software design studies, programming techniques, tables, or spreadsheets [1]. Parametric models are also important so that changes necessary during the design process can be efficiently made [5]. This critical thinking teaching proposal is applicable to a junior level solid modeling course that could be offered in a bachelor's level mechanical engineering technology (MET) program. The goal of the solid modeling course would be to teach the importance of and how to build parametric solid models capturing the design intent of the object or objects being modeled.

By the time students arrive in the course, many are bound to have experience with CAD software and creating solid models. This experience is gained through other courses, hobbies, and work. By observation in the classroom, few students have experience with parametric modeling and design intent as the past focus has been to simply create a solid model of desired shape by any means since the goal is simply to make a model [1].

This paper explores a technique for implementing critical thinking into a solid modeling course to improve teaching the importance of design intent and parametric modeling. Key enablers are to incorporate the critical thinking dispositions of systematicity and analyticity into the process of creating and building parametric solid models and to achieve design intent in the models.

A concept map and a process flow map are presented with the aim of implementing these tools into the teaching of the course. Concept maps (and process flow maps) are visual tools that reinforce the relationship of concepts and provide a framework for thinking and conceptual understanding [2].

Background

Computer aided design (CAD) software is used in the engineering and engineering technology fields to create solid models (models) and ultimately drawings to convey information about inventions and product designs. The activity of creating models is often referred to as solid modeling. The models, and associated drawings, are used for performing design studies, simulations, cost analysis, feasibility studies, design of manufacturing tools and systems, as well as for other forms of analyses and studies.

Design intent "represents what is to be achieved by a design and describes the expected behavior of the model when it undergoes later alteration" ([3], p. 2). It is imperative that solid models are created in a way that they reflect the design intent of the subject being modeled.

Design intent ensures that the item being modeled performs in a way and is dimensionally accurate to perform the function(s) of the intended design. Also, a CAD model build with design intent will behave in a predictable manner when changed, such as maintaining intended relationships between features such as the distance between holes and edges. Here, assignment of part color, part and feature names, and material assignment will be included in design intent.

"Parametric CAD enables the addition of design semantics to the model, which translates into the rapid alteration of existing models by simply editing the values of some parameters" ([4], p. 18). Models also must be created as parametric models. A parametric model is a stable model and will behave predictably when modifications are made to dimensions, features, or other parameters. The predictable behavior can be driven by building relationships, references, and using equations to relate dimensions. Going further, relations between parts in an assembly may be built into an assembly model so that other parts in an assembly will behave predictably when changes are made. Parametric modeling and design intent are closely related, and the focus on design intent is inclusive of parametric modeling on the classroom.

Formally, non-parametric modeling is referred to as direct modeling [5]. In an industry setting where parametric models are expected, direct models are commonly referred to as "hack and whack models" or "dumb solids." It must be mentioned that sometimes direct modeling is acceptable, especially in a rapid prototyping or ideation phase of a project. Choosing when it is appropriate to direct model rather than build parametric models with design intent is a decision that requires critical thinking!

Today, CAD software is widely available, often free, for use by students. It is common for students arriving in the classroom at the Junior class level to have a considerable amount of experience creating models and have been doing so since high school (or earlier). It is the aim of a course to build on existing knowledge and introduce parametric modeling and ensuring that models are created with design intent fully considered. Parametric models and design intent will be new concepts to students in many or nearly all cases.

Preparing students for their future careers is a primary goal in a Mechanical Engineering Technology program. Creating solid models that are not parametric, do not reflect design intent, and simply are not useful other than to convey a shape should result in lower assignment points earned in a classroom setting. In a business setting such as in the engineering practice, useful parametric models are critical, and highly valuable. Solid models can also be costly in terms of time and monetary cost when design intent is ignored and the models not parametric. Determining the cost of non-parametric models is not straightforward and Camba et. al. notes that "a significant amount of time, effort, and resources are spent fixing and rebuilding low quality models, yet no mechanisms are currently available to accurately determine these costs" ([6], p. 635).

Survey of Courses that Specifically Mention Design Intent and/or Parametric Modeling

Institution	Course	Catalog Description Includes: Design Intent	Catalog Description Includes: Parametric	Reference
Purdue University	MET 10200	No	No	[7]
	MET 20400	No	No	[7]
	MET 30200	No	No	[7]
	MET 32800	No	Yes	[7]
Rochester Institute of Technology	MCET 101	No	No	[8]
	MCET 150	No	No	[8]
Ferris State University	ETEC 140	Yes	No	[9]
	PDET 125	No	Yes	[9]
ECPI University	MET 192	No	Yes	[10]
	EET192L / MET192L	No	Yes	[10]
	MET213	No	Yes	[10]
CUNY New York City College of Technology	IND 2340	No	No	[11]
	MECH 1222	No	No	[11]
	MECH 3510	No	No	[11]

Table 1: Catalog description content of courses at five institutions

Catalog descriptions of courses with computer-aided design content in MET programs at 5 institutions were retrieved through web searches and summarized in Table 1, above, for mention of the terms "Design Intent" and "Parametric." The institutions reviewed were chosen at random. Note that the courses investigated are not necessarily all available electives that a student may choose.

Upon review of the curriculum of the 5 institutions chosen, 14 courses (ECPI University's EET192L and MET192L are equivalent) which include computer-aided design were discovered. Of the 14 courses, only ETEC 140 offered by Ferris State University specifically states "Design Intent" in the course catalog description. 5 of 14 of the courses mention "Parametric" in the course catalog description.

Does this mean that institutions are teaching computer-aided design without emphasis on design intent and parametric modeling? A deeper investigation is needed by acquiring syllabi and interviewing instructors to determine the full content. Listing "Design Intent" and "Parametric" in course catalog descriptions might be considered to reinforce course content and convey to potential students and employers of graduates that the concepts are included. It may also aid in course transfers between institutions.

Critical Thinking

Hooks wrote about the dread of thinking:

> By the time most students enter college classrooms, they have come to dread thinking. Those students who do not dread thinking often come to classes assuming that thinking will not be necessary, that all they will need to do is consume information and regurgitate it at the appropriate moments ([12], p. 8).

The regurgitation of information in the solid modeling course is observed as simply the student generating and submitting some model of shape and volume as prescribed by the assignment.

Hooks goes on to describe critical thinking:

> In simpler terms, critical thinking involves first discovering the who, what, when, where and how of things – finding the answers to those eternal questions of the inquisitive child – and then utilizing that knowledge in a manner that enables you to determine what matters most ([12], p. 9).

Rather than simply generating the required shape prescribed by the assignment, a solid model must be built considering the design intent of the part and the model must be parametric. In order to achieve these objectives, the student must think critically about the task at hand (the assignment in this case).

To reinforce the importance of the concepts of design intent and critical thinking, stories from the instructor's industrial experience should be shared (always protecting intellectual property!). "In all classrooms, even in the hard sciences, professors use stories, usually in the form of anecdotes, to illustrate points, to elucidate information that may be abstract.

Story, especially personal story, is one of those powerful ways to educate" ([12], pp. 55-56). Stories can and should be shared that describe the time and labor cost impacts that non-parametric models incur.

In particular, stories will illustrate about how hastily built solid models (direct modeling) may look good and get positive attention for being completed quickly, but do not behave predictably nor reflect the design intent of the object, leading to slower turn around and higher cost for changes to the model. The instructor of the course is likely to have an inventory of these stories from academia and/or industry experience.

Concept Map

To facilitate teaching critical thinking in a solid modeling course, a tool employed will be a process flow map which is derived from a concept map. The dispositions of critical thinking employed in this work are analyticity and systematicity.

Facione et al. describe analyticity as:

> Analyticity is a core disposition for the inquiring mind. Persons with this characteristic are inclined to want to anticipate the consequences of events and ideas, and to use reason, rather than some other strategy to address serious problems as well as entertaining puzzles ([13], p. 5).

This disposition is key for students to question what the design or model is meant to achieve, and to build the solid model in a parametric way such that it will behave predictable and support the design intent of the final product.

"Systematicity is the tendency or habit of striving to approach problems in a disciplined. orderly. and systematic way. The habit of being disorganized is the opposite tendency" [14]. Approaching a solid model in an orderly and systematic way is critical to forming a plan to build a solid model. In many ways, much of the work is done prior to laying down a line in the software!

"Concept maps are graphical representations of cognitive knowledge structures. Although they were originally developed as a way to follow and understand changes in student knowledge, they have proven to be effective instructional tools" ([15], p. 25.1365.2). The decision to use a concept map as a possible tool to teach critical thinking related to constructing parametric solid models was made because it provides a visual framework to guide the student. The concept map being similar or related to a flow charts or block diagrams also introduce students to the methods of making complex processes and relationships visual which is a key skill in industry.

As a more approachable visual, the concept map was organized into a process flow map and serves as a framework that may be used by the students to realize a methodology for constructing solid models. The process flow map is like a memory jogger.

It would be made available throughout the semester (and beyond) for students to refer to in order to inspire critical thinking. An advantage of this is to provide a tool and reduce the burden of memorization.

Concept and Process Flow Maps

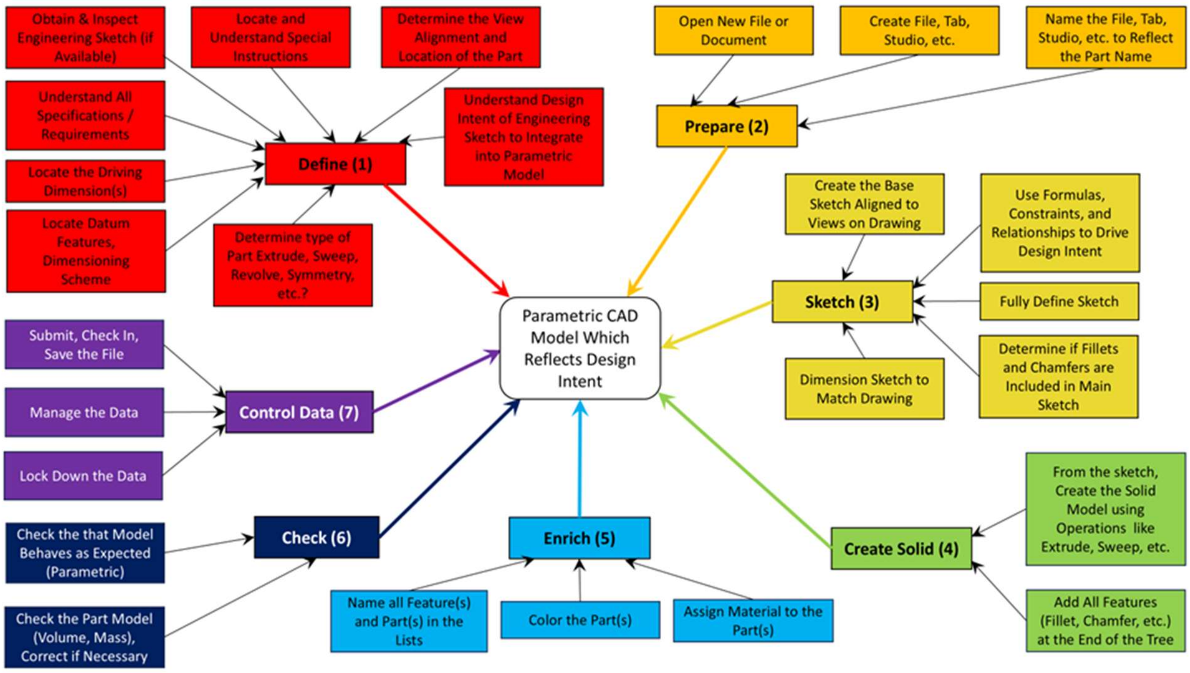

Figure 1: Concept map for parametric solid modeling

Figure 1 shows a concept map for describing the thinking that goes into constructing a parametric solid model that also expresses design intent. The thinking is broken into 7 chunks, Define, Prepare, Sketch, Create Solid, Enrich, Check, and Control Data. The concept map was created based on the author's general understanding of the process of realizing parametric solid models which maintain design intent constructed from ideas. The ideas often are expressed as sketches.

The concept map is used to illustrate thinking of a solid model as a system. Simply creating a solid model that represents the desired shape with features and satisfies only one or a few of the 7 chunks does not create a wholistic and useful model. In the big picture of the business of design and engineering systems, the solid model is a part of the whole system. The solid model is in itself a system of thinking and details that come together to provide a subsystem to the larger system. The concept map is the visual tool chosen to illustrate the system of a model as it is understood.

Figure 2 shows the concept map re-written into a process flow map which is the main tool to be used in teaching. The 7 chunks are the same, and rearranged into a linear flow. One difference is that in chunk 3, *Sketch*, the flow map is decision based to encourage self-checking of work.

The comment “Do no math” is related to the teaching method used. In teaching parametric solid modeling, drawings with dimensions are provided to students. The parametric solid model is to be constructed using only dimensions given, preserving the design intent expressed or communicated by the dimensions.

This is not always straightforward! Students who just want to get done quickly and achieve the shape of the model will create new dimensions that do not exist on the drawing or eliminate dimensions by “doing math.” This (almost) always leads to models that are not parametric, or hack and whack models that do not behave predictably, and also do not maintain design intent of the part design.

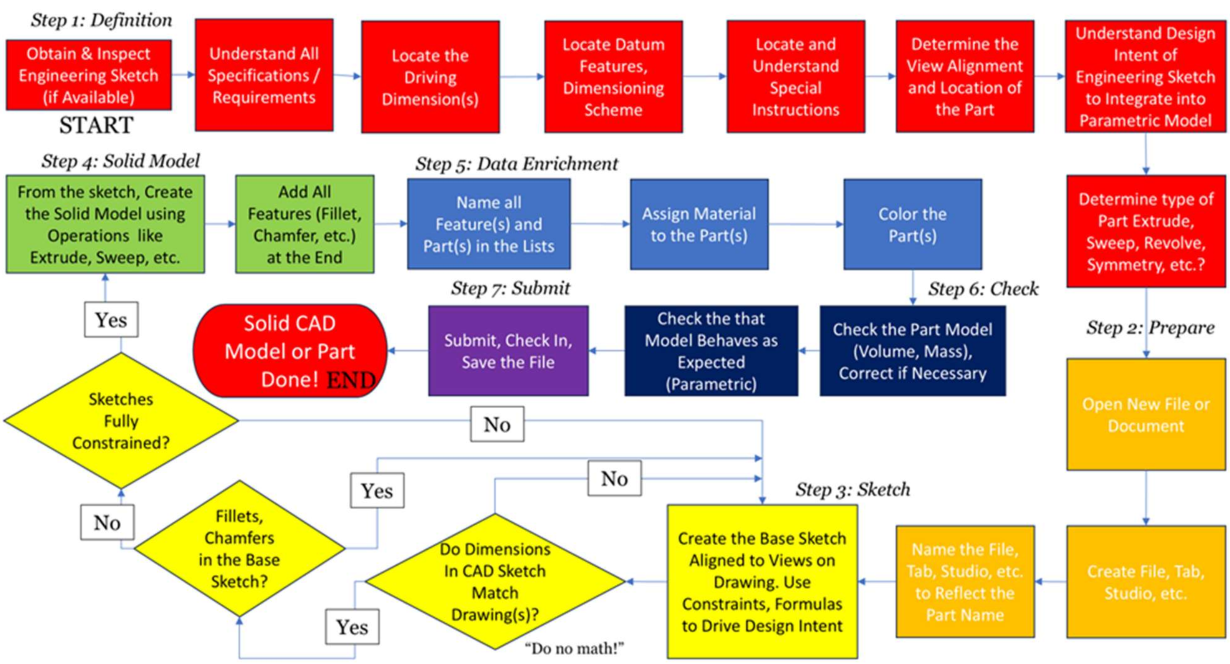

Figure 2: Process flow map

Upon inspection of the concept map in Figure 1 and the process flow map in Figure 2, one will quickly realize that there are a lot of details included that are not explicitly addressed in this work. In practice, the maps can be made more or less detailed to fit a particular situation in a classroom or when applied in a business setting. The maps serve as visual tools to express the many steps and built-in detail that is required to create a useful parametric model which reflects design intent. Skipping or missing details will result in models that ‘break,’ do not behave predictably, do not contain information required for further analysis, and in the end generate non-value-added rework or rebuild of the models.

Methodology for Teaching

The methodology to be used in the classroom to teach critical thinking in modeling with design intent consists of:

i. Integrated lecture and lab. Provide students with the process flow map.
ii. Providing a parametric CAD modeling software for students to use.
iii. Providing drawings and/or detailed instructions of parts and assemblies for students to model.
iv. Deliver a number of instructor led and independent student assignments.
v. The assignments to be assessed per a rubric designed according to the process flow map.

When creating solid models, it is important for the person doing the work to interpret specifications and instructions and implement them into a parametric model while ensuring design intent. The space that exists between interpretation and implementation requires critical thinking.

If the act of solid modeling is thought of as a process, the aspects and tasks required to create a solid model can be listed and employed in an organized and systematic manner. Depending on the practitioner and the CAD software used, the aspects and tasks may be organized in a way that best suits the practitioner's approach and/or the CAD software functionality. No matter the order or the CAD software, the result will be the same.

"Because the process of design is a main focus of most 4-year programs in engineering technology, it is essential that students be taught the skills that will make them proficient in design" ([16], p. 6.808.1). In the type of course that is the subject of this work, it is assumed that the course would be the first time students are exposed to the concepts of design intent and parametric modeling. With this assumption in hand, the course may be designed to teach these skills using pre-defined designs. The skills will then transfer to designs the students synthesize themselves.

By using pre-defined designs, students are not challenged with the burden of coming up with new designs which enables focus on learning the key thinking concepts and skills. As students progress in their program of study to the time where they are required to execute a capstone design project, they will be required to synthesize new designs themselves.

The critical thinking skills learned prior will enable their success in their capstone projects, and ultimately, the goal is enabling students' success in their careers. This is a scaffolded approach that is intended to teach critical thinking in solid modeling first, and carry this knowledge into actual modeling of parts synthesized by the students.

Rubric and Assessment

Rubrics are tools that are reliable for grading and are valuable teaching and learning tools [17]. A rubric that is aligned with the process flow map shown in Figure 2 is presented in Table 2 (on next page). This rubric to be used for assessment of student work and may be provided to students as part of the assignment materials. The rubric is broken down into 5 criteria that are aligned with the process flow map. Each criterion is rated Excellent, Good, Developing, and Poor. Points may be assigned to each criterion for assessment rating.

Chunking the rubric allows assessment for each section of the process flow map. This allows the student to receive feedback on the different chunks. It is plausible that a student could do well in one area and not as well as another. For instance, if a student simply built a 'hack and whack' model, they could earn an 'Excellent' rating in the 'Steps 6 & 7' criteria and a poor rating in the other criterion. Ideally, feedback such as this to a student would encourage a critical thinking approach encompassing the entire process flow map on future exercises.

For students, the rubric provides an outline of how the work will be assessed. The combination of the process flow map and rubric outlines the expectations and both serve as reminders of what must be considered when thinking about the work as well as expectations.

For the instructor, the rubric serves as a guide to facilitate consistency in assessment between students and across assignments. Having the assessment separated out into chunks allows the instructor to provide feedback in each of the seven flow map chunks to focus students on improvement areas.

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	Ratings			
Criteria	Excellent	Good	Developing	Poor
Steps 1 & 2: Preparation Models oriented in space to match the given instructions. Parts located per assignment instructions. Part file, tabs are named.	Modeling is correct and appropriate	More than 50% of the modeling, but not 100% is correct and appropriate	Less than 50% of the modeling, but not 50% is correct and appropriate	Assignment or work is missing
Step 3: Sketch Creation All sketches are fully defined, dimensioned, and constraints applied. Fillets, chamfers, grooves, and undercuts are created as features or sketched according to design intent (with sketches at the end of the feature tree facilitating solid model feature creation). Dimensions match instruction, no mathematical manipulation done. Design intent / parametric modeling.	Sketching is correct and appropriate	More than 50% of sketching is correct, but not 100% is correct and appropriate	Less than 50% of the sketching, but not 50% is correct and appropriate	Assignment or work is missing
Step 4: Solid Model Creation Solid model generation is consistent with part type (i.e. extrude, sweep, revolve, etc.). Solid model creation matches design intent, model is parametric. Features like fillets and chamfers added at end of tree.	Solid modeling is correct and appropriate	More than 50% of solid modeling is correct, but not 100% is correct and appropriate	Less than 50% of the solid modeling, but not 50% is correct and appropriate	Assignment or work is missing
Step 5: Model Enrichment Features named, parts named. Material assigned to models. Configuration table aligns with instructions. Part configurations are placed in assembly tab. Color assigned to part other than default color.	Model enrichment is correct and appropriate	More than 50% of model enrichment is correct, but not 100% is correct and appropriate	Less than 50% of the model enrichment, but not 50% is correct and appropriate	Assignment or work is missing
Steps 6 & 7 Part volume matches the drawing or instructions. All models completed and turned in if multiple models.	Modeling is correct and appropriate	More than 50% of modeling is correct, but not 100% is correct and appropriate	Less than 50% of the modeling, but not 50% is correct and appropriate	Assignment or work is missing

Table 2: Assignment Rubric

Potential Barriers to Learning

The solid modeling course that critical thinking is to be implemented in is likely a junior level course in the Mechanical Engineering Technology program. By this time in their education, many students are likely to have been exposed to CAD and solid modeling, possibly for a number of years and often from the time they were in high school. Additionally, in many degree programs, there is often a freshman engineering graphics course that the students have completed that has a component of solid modeling, but without focus on design intent and parametric solid modeling [1]. This prior experience can lead to bias.

The bias is a recollection that acceptable performance was achieved without thinking critically and incorporating parametric modeling and design intent, so why start now! Thinking that past performance is good enough going forward can lead to a barrier and possibly resistance to learning the new concepts.

Expected Results of Implementation

If the ideas presented in this paper were implemented in the classroom, would they make a difference or improve critical thinking related to building solid models? Zhou et al. conducted research aimed at measuring the change in critical thinking in a chemistry classroom using teaching techniques [18]. The research used two ways of measuring critical thinking. Of interest here are the results from California Critical Thinking Disposition Inventory (CCTDI) that Zhou et al. employed before and after a period of classroom teaching [18]. The CCTDI results are of interest here because it includes measures of the critical thinking dispositions of analyticity and systematicity, both of which are two dispositions employed in this proposal.

Upon conclusion of their research, Zhou et al. found significant changes in both analyticity (A) and systematicity (S) as shown in figure 3 [18]. The y-axis of the chart is the score for each category.

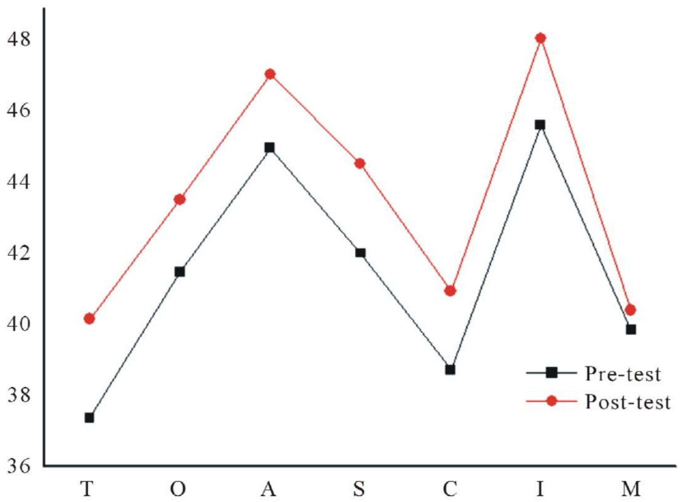

Figure 3: Zhou et al. CCTDI results. Note: T = Truth-Seeking; O = Open-Mindedness; A = Analyticity; S = Systematicity; C = Self-Confidence; I = Inquisitiveness; M = Maturity. [18].

Although the work of Zhou et al. was done in a chemistry classroom, the results may be considered predictive of the outcome in the solid modeling course using the proposed methods in this paper. Zhou et al. incorporated a web-based teaching and learning platform into the classroom as a teaching approach and measured significant differences in five of seven critical thinking dispositions [18]. Incorporating pre-defined design lessons along with the process flow map in a solid modeling course can reasonably be expected to yield a similar result.

Conclusion

When critical thinking is encouraged in a solid modeling course, students will learn new ways to think about how models are built. Ensuring the use of parametric techniques and ensuring the incorporation of design intent of the part or system being modeled will build the engineering thinking needed to facilitate success in a career. Beyond a solid modeling course, the ideas illustrated in this paper may be applied to any number of course topics as illustrated in Lofton's work which implements concept mapping in a heat transfer course [2].

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