



Solid Modeling Strategies – Analyzing Student Choices

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Abstract

There is an increasing trend in solid modeling instruction to include not only procedural knowledge but also strategic knowledge when teaching students how to build solid models. In order to evaluate the many choices made by students as well as experts in their modeling procedures, and to compare different types of solid models used in these studies, it is necessary to measure various parameters associated with model complexity and “goodness” of the solid model. In this paper we will propose metrics for evaluating solid models such that different modeling strategies can be compared. Furthermore, we will compare the models created by students who are given different strategic instructions for modeling, as well as the results of change exercises implemented in upper division solid modeling courses.

Introduction

Solid modeling instruction must include not only declarative and procedural knowledge but also strategic knowledge when teaching students how to build solid models¹⁻⁴. In the context of solid modeling, declarative knowledge includes facts such as the types of features that can be used to build a solid model, the types of geometric constraints used to control sketches, dimensioning rules, etc. Most current engineering graphics texts include this type of information⁵⁻⁸. Procedural knowledge focuses on how to perform various functions or utilize the commands in a particular solid modeling system. This type of information can be found in any of the typical introductory CAD tutorial texts or manuals⁹⁻¹¹, as well as online learning available from the software vendors^{12,13} or independent sources such as YouTube¹⁴.

Effective use of CAD systems also requires the acquisition of strategic knowledge such as selection of solid modeling alternatives and proper use of modeling constraints to capture design intent²⁻⁴. Two schools of thought dominate the strategic approaches used by instructors as well as practicing designers – efficiency and flexibility. An efficient model is one which can be created quickly by the designer and results in a smaller file. A flexible model is more easily changed by the designer or others who utilize the model in downstream applications. Both strategies seem to be widely used, although it is not clear whether one approach is better than another, or under what circumstances each approach is favorable. Bhavnani et al.¹⁵ and Hamade et al.¹⁶ favor fewer, more complex features, as these parts can be modeled more quickly. On the other hand, Rynne & Gaughran⁴ and Chester^{2,17} recommend simpler sketches for parts which are more easily modified. Wu¹⁸ stresses that the best strategy for modeling more complex parts may not result in the smallest number of features, and that overall efficiency of model use depends not only on the speed with which the original model is made, but also the ease of changing the model. Ault & Giolas¹⁹ found that practicing designers used both strategies. Furthermore, these designers rationalized their selection of modeling strategies as a combination of habits or personal preferences, company standards, and capabilities or limitations of the software. Johnson et al.²⁰⁻²³ add another consideration – easy to understand – since the model will be used by others during the product development. Using clearly named features rather than the default generic labels and logical grouping of features can facilitate understanding of the model by others.

Solid modeling strategies are often described as a means to “capture design intent”, but the interpretation of this phrase is rarely explicitly stated. Barnes et al.²⁴ describe design intent as the intelligence built into the solid model to control the behavior of the part when subjected to changes or alteration. However, it is difficult to predict what types of changes a part may undergo during product development. New part design often encounters both dimensional and topological or feature changes. Selection of the dimensions as well as part features should reflect the important functional requirements of the part.

Most solid modeling exercises found in CAD tutorial texts are presented as either orthographic or isometric drawings of existing parts. Kirstukas²⁵ explains that design intent can be inferred by careful inspection of the part drawing. The solid model should utilize only those dimensions (parameters) found on the drawing, as these dimensions were selected by the original designer to capture functional requirements of the part. The modeler should not need to compute additional dimensions to create the solid model, nor should dimensions be repeated in the model. The modeler should be able to reproduce the part using the given dimensions and suitable geometric and algebraic constraints. In Ault & Giolas’¹⁹ interviews, practicing designers identified a correlation between the modeling parameters and the dimensions on the 2D drawings. Devine & Laingen²⁶ propose assessment of student models by comparing the list of parameters to the dimensions on the given drawings. Numerous instructors report that assessing student models should include changing the model parameters or “flexing” the model.^{1,19-28}

Salehi and McMahon²⁹ surveyed CAD users in the automotive industry and found that the users identified a lack of methodology to select the necessary parameters and associative relationships in their solid models. This strategic knowledge requires higher level thinking skills associated with decision making, or knowing about available alternatives and how to choose between these alternatives. Thus, it would seem that experience is an important aspect in the development of modeling strategies.

Barnes et al.²⁴ suggests that many of the exercises presented to students are in the form of “elegant solutions” which present essentially one single obvious modeling approach. Fortunately, even very simple parts such as those presented in standard graphics texts can be modeled using different strategies. In planning a part model, the designer must decompose or “featurize” the part to be created in the solid modeling system. Two common strategies for modeling simple parts involve decomposition into features based on either additive or subtractive approaches.³⁰

Metrics for Evaluating Solid Model Part Complexity

It is important to choose parts for CAD instruction that present increasing levels of complexity as well as alternative feature selection. How complex is the part? Is the model an “elegant solution” or are there many possible solutions? How much do these different solutions affect the efficiency or flexibility of the model? Each of these questions must be considered when choosing parts which will enhance students’ strategic modeling skills.

One measure of the complexity of a model is the number of features in the model tree. However, a simple count of the number of features in the model tree may be a poor measure of the model complexity. Features can be grouped into three categories: sketched features such as extrusions and revolves, form features such as holes, and edge features such as rounds and chamfers. In

addition, geometry can be duplicated using patterns and mirror options. Complexity of sketched features can vary based on the number of entities in the sketched profile and the number of sketches (for swept and blended features). Edge features may be applied to multiple edges, in sets with common parameters. Johnson et al. include the following counts in their comparison of different modeling strategies: number of features, average number of entities in each sketched feature or number of edges in round and chamfer features, number of patterns, and number of mirror features²⁰⁻²³. Since all of their studies utilized the same part, these factors were each considered separately in the modeling strategy comparison, and there was no need to consider the complexity of the part itself.

Another measure of complexity could be the number of parameters or dimensions in the model. However, as noted previously, some dimensional constraints could be replaced with geometric constraints on the same part, depending on the design intent. Kirstukas²⁵ demonstrates this with two different versions of the same part, one of which has eight dimensions and the other nine, as seen in Figure 1. Other non-numeric feature parameters might include such characteristics as the terminal conditions for protrusions and holes.

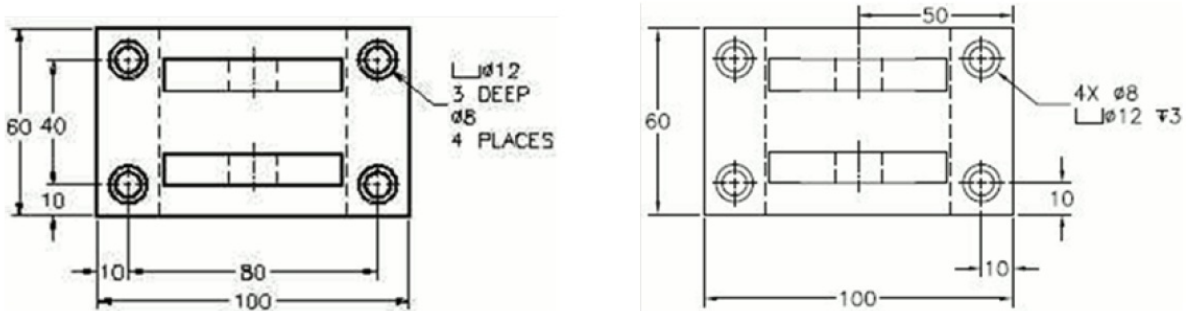


Figure 1. Part with different dimensioning schemes and parameter count (Kirstukas²⁵)

Datum features may or may not be included in the feature count. The need for datum features may be due to differences in modeling systems; for example, some systems will recognize the axis of any circular edge whereas others will need to have this axis explicitly defined before using it as a reference for other geometry construction. Ault & Giolas¹⁹ noted that some designers prefer to base sketches on datum planes rather than existing planar faces; this strategy has also been promoted as a means to unlink the associative parent/child relationships in a solid model. If the goal is to measure the complexity of the basic geometry, then the datum features would only be used to facilitate different modeling strategies or system requirements and do not affect the basic geometric form of the part and should therefore not be included in the complexity measure.

Based on these observations, the authors propose the following equation for computing the part complexity index (CI):

$$CI = \sum_{i=0}^{F_S} E_i + \sum_{i=0}^{F_E} \sum_{j=1}^S N_{ij} + \sum_{i=0}^{F_H} C_i + \sum_{i=0}^{F_M} CI_i + \sum_{i=0}^{F_P} CI_i \quad (\text{Eq. 1})$$

Where:

- F_S = number of sketched features (extrude, revolve, sweep, blend)
- E_i = number of entities in the associated sketches for the i th sketched feature
- F_E = number of edge features
- S = number of edge feature sets
- N_{ij} = number of selected edges for the j th edge feature set within the i th edge feature
- F_H = number of (individual) hole features
- C_i = hole complexity factor for i th hole (simple holes = 1, countersunk or counterbored = 2)
- F_M = number of mirror features -1
- F_P = number of pattern features -1
- CI_i = Complexity index of features patterned or mirrored in the i th pattern or mirror feature

The proposed algorithm has been applied to parts utilized by various researchers in their studies that have been modeled using alternative modeling strategies. Kirstukas²⁵ uses a simple plate with hole features and standoffs, shown in Figure 1. Johnson¹⁷ uses a similar baseplate part with more slots, mirrored or patterned features and standoffs, shown in Figure 2. The goal is to develop a measure of part complexity that is independent of the modeling strategy used.

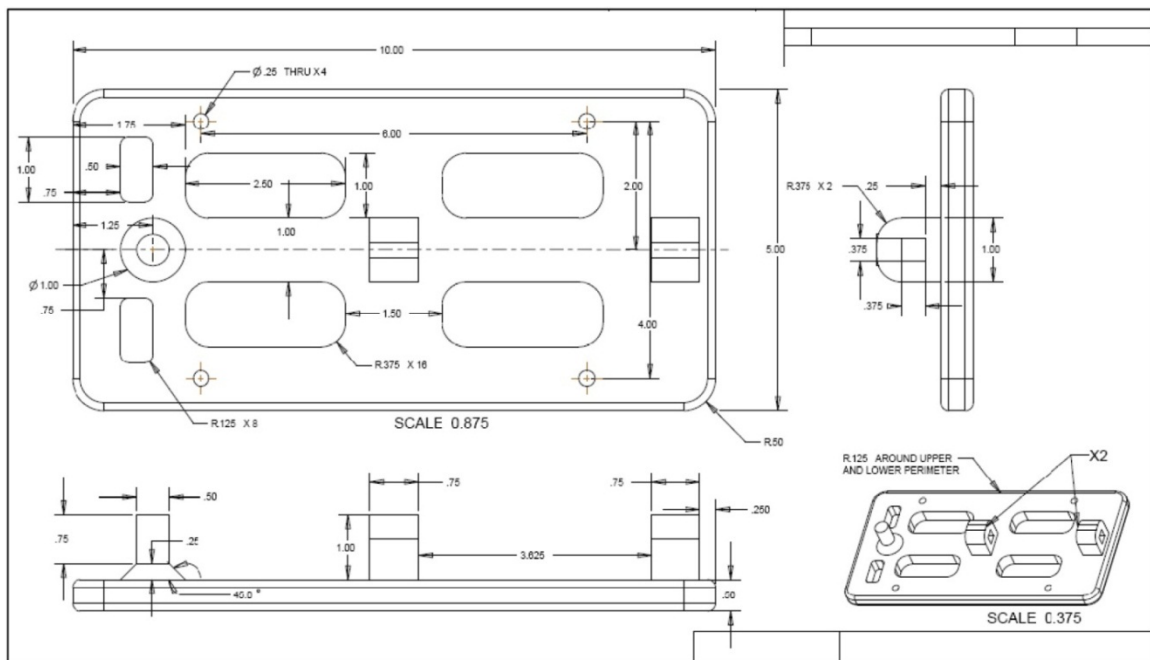


Figure 2. Baseplate part used for modeling strategy comparisons by Johnson et al.²⁰⁻²³

Each of the parts was modeled using a minimum number of features with complex sketches, including rounds in the base sketch (K1 and J1). This strategy conforms to the approach promoted by Bhavnani et al.¹⁵ and Hamade et al.¹⁶ for efficiency. The model tree and part K1 are shown in Figure 3. The model tree and base sketch for part J1 are shown in Figure 4. Dimensions and constraint symbols have been hidden for clarity. The complex sketch for this base feature contains 56 entities; the model contains only 4 sketched features, two copy features, one hole and one edge feature.

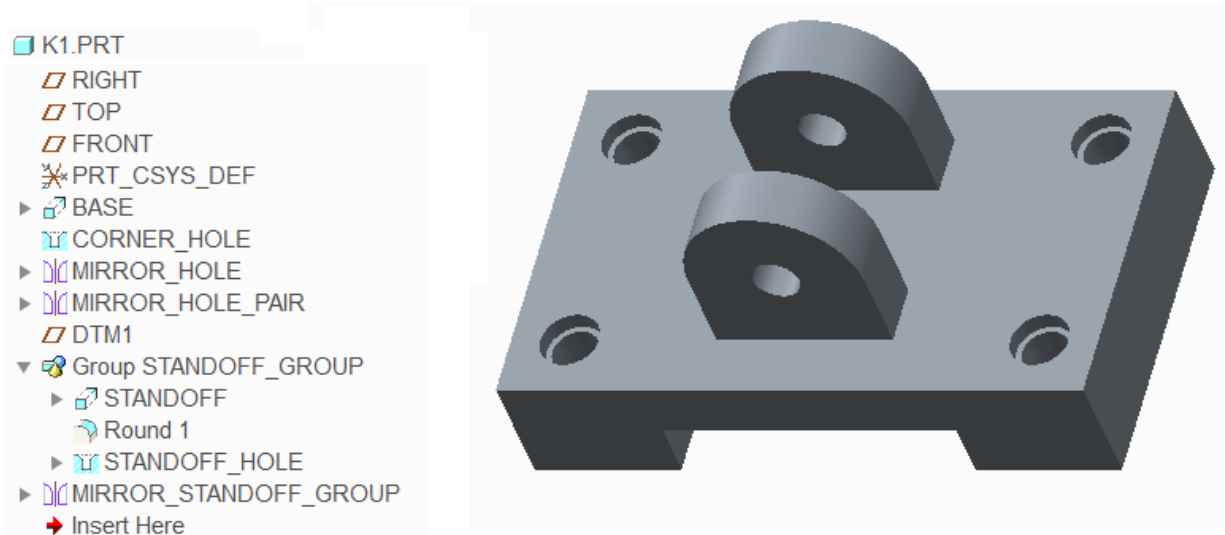


Figure 3. Model tree and K1part

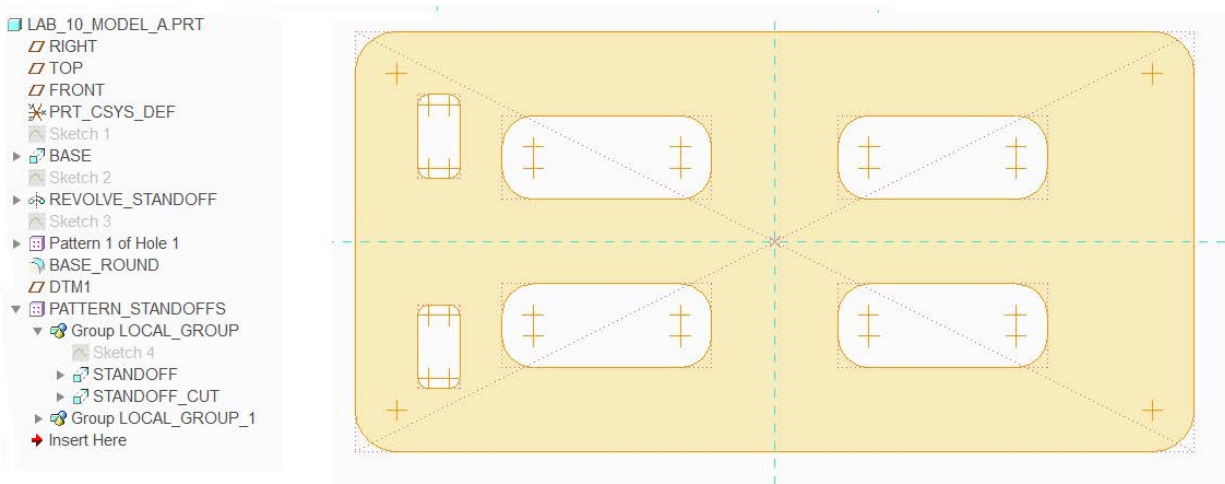


Figure 4. Model tree and base feature sketch for Johnson Baseplate J1 strategy

The parts were also modeled using a larger number of simpler features (K2 and J3), to provide more model flexibility for alterations, as recommended by Rynne & Gaughran⁴ and Chester². Figure 5 shows the model tree and base feature for this modeling strategy. The simple sketch for this base feature contains only 4 entities; the model contains six sketched features, five copy features, one hole and four edge features.

The Johnson part was also modeled with an intermediate strategy (J2), which contained 5 sketched features, 4 copy features, one hole and one edge feature. Two additional parts were modeled to determine whether the feature types would affect the complexity index calculations. Part A, shown in Figure 6, was modeled using only extrusions for A1, and a combination of revolve and extrude features for A2. Part B, shown in Figure 7, was modeled using only extrusions for B1 but included a blend feature for B2. Results of the complexity calculations for

parts modeled with these alternative strategies are shown in Table 1. Note that parts K and J were modeled using the same collection of features for the chosen geometry (largely extrusions). For these parts, the CI remains unchanged, as the variations in the number of features and entities in each feature results in the same product sum. However, in the case of part A, substituting a revolved feature in place of an extruded feature increases the CI, as there are four entities in the rectangular sketch required to revolve a cylinder as compared to the single circle used to extrude the same cylinder. Similarly, use of the blend feature instead of an extrusion increases the CI for part B.

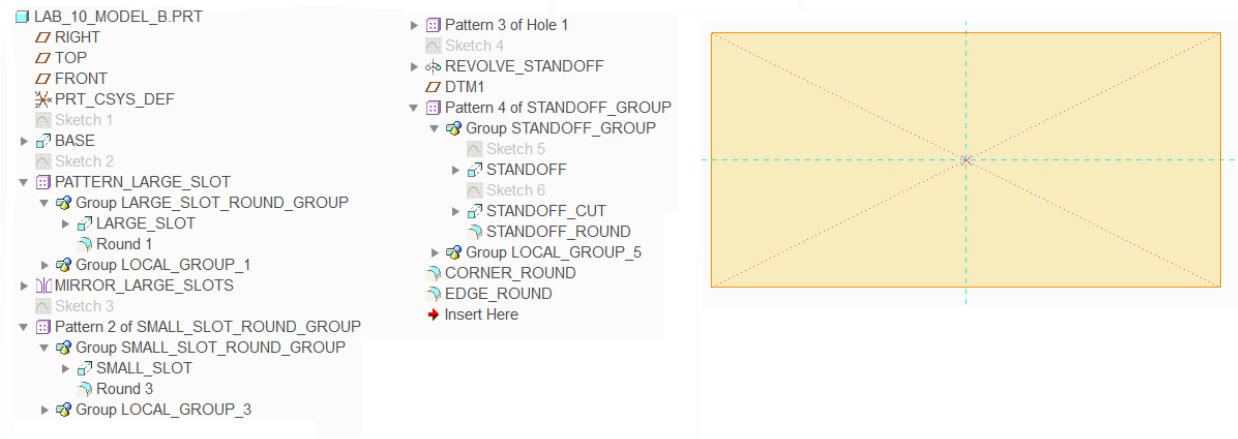


Figure 5. Model tree and base feature sketch for Johnson Baseplate J3 strategy

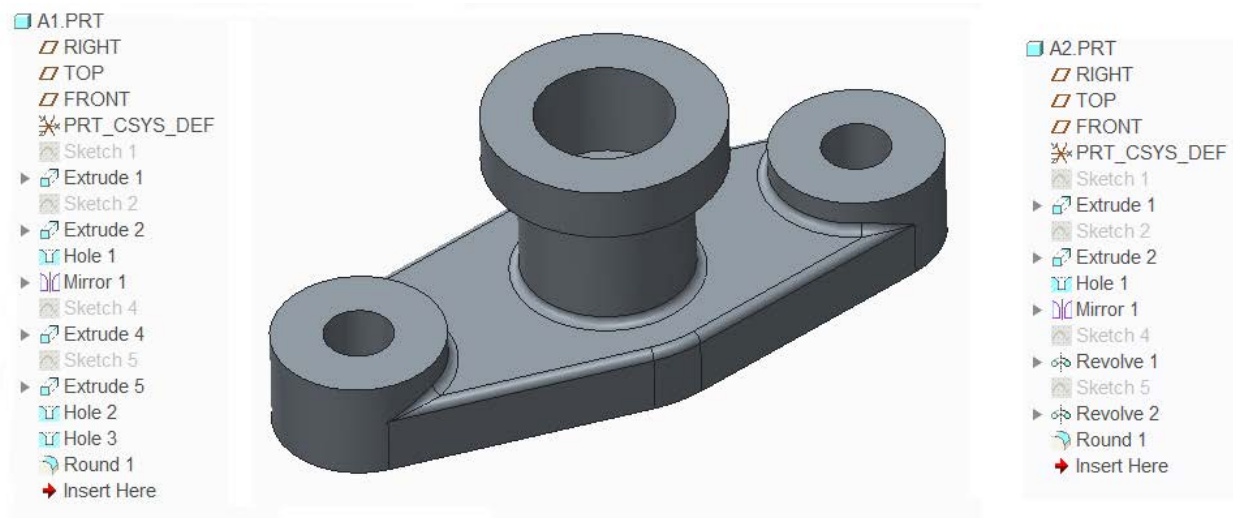


Figure 6. Part A with two modeling strategies

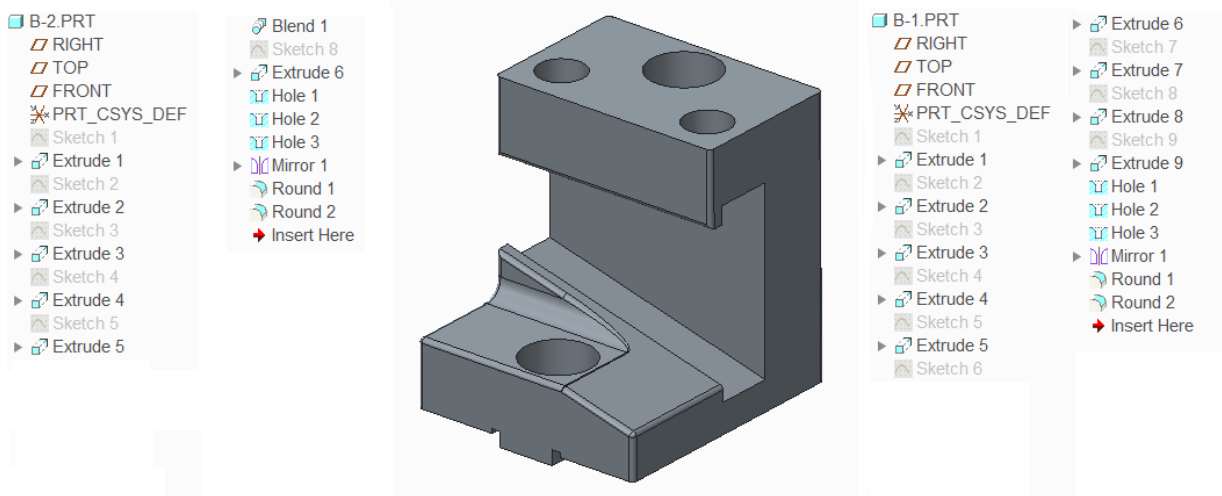


Figure 7. Part B with two modeling strategies

Table 1. Measures of part complexity

	F _S	F _E	F _H	F _M	F _P	CI
K1	2	1	2	5	0	30
K2	3	1	2	3	1	30
J1	4	1	1	0	2	101
J2	5	1	1	0	4	101
J3	6	4	1	1	4	101
A1	4	1	3	2	0	26
A2	4	1	1	2	0	34
B1	9	2	3	1	0	61
B2	8	2	3	1	0	66

The Complexity Index measures can be compared to the data collected using Johnson's comparators of number of features, average number of entities in each sketched feature or number of edges in round and chamfer features, number of patterns, and number of mirror features, as shown in Table 2. Johnson et al.²⁰⁻²³ observed that experts' models had fewer, more complex features, such as models K1 and J1.

Other factors associated with the quality of a modeling strategy include the correct placement of the part origin and orientation of the model within the global coordinate system. Proper placement of the part facilitates use of the global datum planes to capture symmetry and creation of correct drawing views. Feature order and feature termination characteristics are also important to capture design intent and create a robust, flexible model^{18,20,25}. These factors are not a measure of the part complexity but do contribute to the robustness and usefulness of the model in downstream applications.

Table 2. Johnson's comparative part measures

Part	# Features	Avg. # edges/ sketch feature	Avg. # edges/ edge feature	# Patterns	# Mirrors
K1	10	4	2	1	3
K2	10	6	2	0	5
J1	9	17.75	16	3	0
J2	11	7.8	16	8	0
J3	22	4.17	6	4	2

Prior Research on Student Change Modeling Strategies

Student choices often depend on experience. In particular, modeling for flexibility is often overlooked by students, who are usually taught simply to duplicate a given part geometry. Part modifications, if assessed, usually involve dimensional changes only. Students are seldom exposed to exercises that require part feature modifications, and therefore have little experience in inspecting, assessing and making changes to existing models. These students will utilize a “brute force” approach rather than a strategic approach to making necessary design changes. Johnson et al.²⁰⁻²³ have conducted some studies to assess student modeling strategies associated with change, including both dimensional and topological changes. This paper extends the investigation using the same part, shown in Figure 2, including Johnson's changes as seen in Figure 8. Dimensional changes are highlighted in yellow. Topological changes include removal of two slots, changing two round features to chamfers, and changing the geometry of two of the standoff features (circled in red).

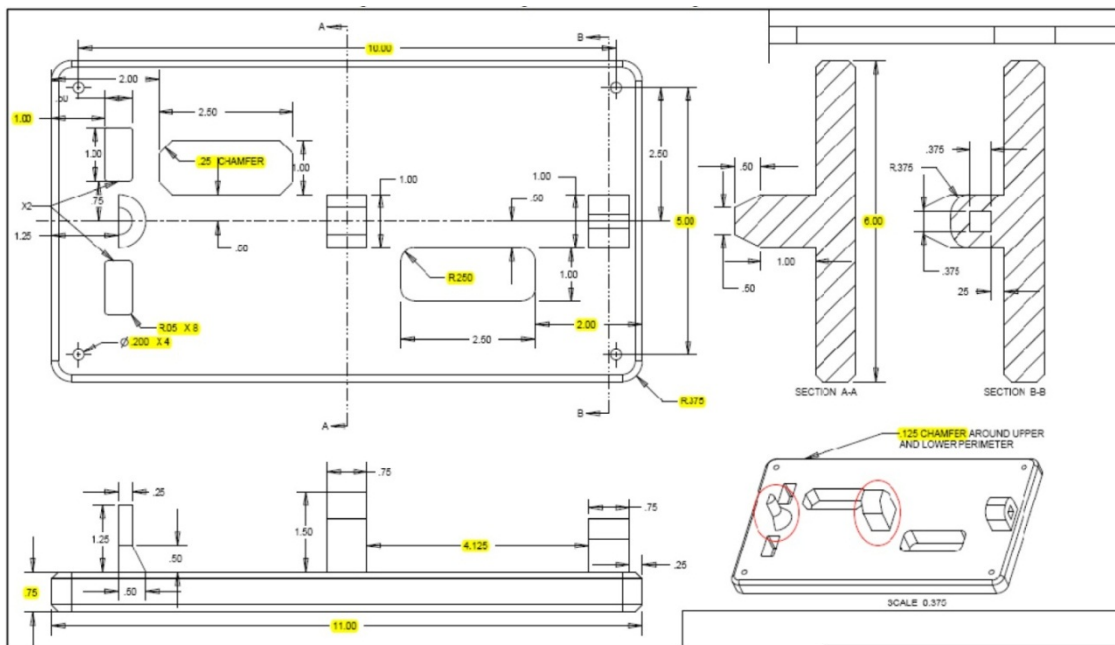


Figure 8. Dimensional and topological changes to Johnson's baseplate model²⁰⁻²³.

As a measure of the change, Johnson recorded the numbers of new features, deleted features, changed features and unchanged features, as well as the percentage of retained features (changed or unchanged). In a series of studies, the researchers compared modeling strategies of students and experienced designers in creating the original part as well as making modifications to different versions of the original part.

Observing Student Change Strategies

In order to study student modeling strategies for creating and altering models, two classes were selected for comparison. One course is a second level advanced CAD course for upper division mechanical engineering students using PTC Creo (32 students) with a focus on extending the students' modeling repertoire and using the solid models in simulation and design analysis applications. The second course was a graduate level CAD course focusing on geometric modeling with more emphasis on theory and mathematics (19 students). The graduate students were allowed to use any available CAD system based on their past experience; most chose SolidWorks, with a few students using PTC Creo. Students in both courses participated in a lab exercise similar to the Johnson studies²⁰⁻²³. The students were assumed to be familiar with the modeling software and were able to justify the strategies they used during the experimental lab.

As in the Johnson study¹⁷, the graduate students were instructed to build the part shown in Figure 2, with half of the class instructed to model based on speed and efficiency and the remaining half of the class instructed to build a robust, flexible model that would accommodate design changes. Students were given one hour to complete the initial model, and completion times were recorded. In the second part of the lab, the students were asked to make design changes as shown in Figure 8. Unlike the Johnson study²⁰⁻²³, the second phase of the lab utilized parts that were modeled by the instructor rather than models created by their peers. Half of the students in each group were given easy-to-change parts (similar to J3) and the other half were given efficiency parts (similar to J1), both modeled by the instructor. Students were again given one hour to complete the model changes and times for completion were recorded.

For the undergraduate course, the exercise contained 4 phases, one before the lab and three during the lab period. In phase one, the students were told to create a model of the part shown in Figure 2 using their own strategies, and no other information was provided to influence their modeling strategies. Johnson¹⁷ reported that many of his students were unable to complete the modeling task within the allotted time (50 minutes), so we elected to allow the students to model the parts outside of class to allow as much time as needed. Modeling times were not recorded. In phase two, during the first hour of the lab, the students were given models of the same part created by the researchers using three different strategies (J1-J3). The given models were created using features for flexible modeling (J3), efficient modeling (J1) and a combination of flexible/efficient modeling (J2) as noted above. The students were told to inspect and study the models and compare to their own model. Some hints were given to help the students assess all the models, such as feature numbers, complexity of the sketches and different options for specific features. In phase three, the students were told to modify their own parts according to Figure 8. The students were assumed to use what they learned in the inspection phase to modify their model with suitable features. And in the last phase the students were told to choose one of the given models from phase two, with the chosen model which was most different from their own model, and to modify according to Figure 8. The times were recorded during phase three

and four as well. After the lab, the students were asked to answer a few multiple choice questions and also write a brief report about what they learned during the lab.

To compare the data, the students were sorted by their self-reported level of experience using CAD software.

Level 1: introductory CAD courses only

Level 2: introductory CAD courses plus infrequent use in class projects

Level 3: 1-2 years of frequent use in an academic setting

Level 4: extensive experience, including industry or internship

By comparing these different levels of students with their own models and modified models, it is possible to explore and study how students justify their modeling strategy when they create and modify a part.

Student Approaches to Original Part Modeling

In accordance with the strategies recommended for a more robust, *flexible* model, one would expect the models to include more, simpler features as well as hole features, mirrors, patterns and edge features whenever possible. Complex sketches should be avoided to facilitate model changes. For a more *efficient* model, one would expect fewer features.

Table 3 shows results for the original models created by both graduate and undergraduate students, along with the J1 (efficiency) and J3 (change) models created by the researchers. Students with industry experience tended to create models that are more efficient, with fewer sketched features and fewer copy features, indicating that their sketches are more complex. These experienced students also used more edge features, suggesting that they recognize these as secondary elements of the geometry which are more easily modeled as 3D “algorithm” features as compared to 2D sketch features. It is interesting to note that these strategies are similar to those observed by other researchers who have investigated modeling strategies of expert CAD modelers in industry. The average number of features for all student groups was comparable to the number of features in the instructor-modeled J3 part, with slightly higher number of sketched features and slightly fewer copied features.

Table 3. Part model creation statistics for student models

Experience Level	# students	Avg. Total # Features	Avg. # Sketched Features	Avg. # Copy Features	Avg. # Edge Features
1	10	13.8	6.0	3.7	1.8
2	12	12.8	5.6	4.5	2.2
3	4	15.0	6.3	4.5	2.0
4	6	12.0	5.0	3.0	2.7
Grads (speed)	6	10.7	5.0	0.8	3.3
Grads (change)	8	14	5.9	1.9	3.7
J1	--	7	3	2	1
J3	--	12	5	5	1

Upon inspection of the original models created by the graduate students, we concluded that these students typically used the same strategies regardless of instructions given. It may be noted that the nineteen students ranged widely in experience, including five students who had only a basic introductory CAD course and infrequent or occasional use, and five students with extensive work or project experience; the distribution of student experience between the groups was not controlled.

Student Strategies for Part Changes

Change exercises also demonstrated differences in outcomes based on the skill levels of the students as well as the starting point for the given change. Results for the undergraduate students using the instructor-provided models are shown in Table 4. Note that only one student chose the J3 model to change. The J1 model originally contained only 7 features, as compared to the J2 model with 12 features. The J1 model is most unlike the original models created by the students, which had an average of 13 features. With fewer features available in the J1 model, the number of changed and deleted features was lower than for the J2 model. Interestingly, the number of new features needed for the J2 model is also higher. While there are some differences between students with varying skill levels, the primary differences are based on the part selected for modification.

A more detailed inspection of individual part files is needed to determine the types of changes made by the students, whether these changes are simple dimensional variations, or changes to sketch entities or other feature characteristics, and how their part modification strategies vary based on the types of topological changes needed.

Table 4. Part modification statistics for undergraduate students

Experience Level or Part Chosen	# Students	# New Features	# Deleted Features	# Changed Features	# Unchanged Features
1	10	2.9	2.1	5.0	2.8
2	12	4.25	2.92	6.83	3.17
3	4	4.75	3.0	5.75	2.5
4	6	3.5	4.0	5.5	2.5
J1	22	2.77	1.73	4.68	2.59
J2	9	5.89	5.78	8.67	3.56
J3	1	6	2	7	2

Student comments were interesting in that the exercise received mixed responses regarding sketch complexity and preferred modeling strategies. One student recommended “leaving whatever complexity I can out of sketches and incorporating them into additional features when possible so they can be modified easier” whereas another observed that “round and chamfer features within the sketch are both slightly easier to create and to modify”. When asked whether they were influenced to change their modeling strategies based on the experience of inspecting and modifying these parts, some students suggested very specific strategies:

- “In future models I will be sure to construct my rounds and chamfer features at the end of my modeling process.”
- “The main strategy I am going to do is naming the features I make. I am also going to start using chamfers and rounds as a feature.”
- “In the future, I will try not to group up different features in a mirror so that I could change the part if necessary.”
- “After seeing how useful mirror is in the past few labs, I will certainly employ more use of that feature.”

A few reflected on the situational aspects of modeling strategy: “I would certainly use different modeling strategies depending on the intended future of a particular part file.” Some of these comments may reflect the students’ inexperience with changing models, as it was observed that many students immediately opened the sketches to make simple dimensional changes rather than using the edit function for part parameters.

Conclusion

Instruction of students regarding part modeling strategies to capture design intent continues to evolve, even as the solid modeling systems become more complex and users in industry develop best practices. Intentional exercises to make students aware of the need for careful part planning should include more strategic discussions regarding the uses of part models and alternative methods. Models used for these exercises need to be sufficiently complex to challenge students’ ability to decompose parts and consider alternative modeling strategies. There is no single correct answer regarding part modeling strategies, and students must rely on experience and situational decision making to build robust solid models.

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