Title:
**The Cost of Change in Parametric Modeling: A Roadmap**

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Introduction:
One of the most celebrated advantages of parametric feature-based 3D modeling is the ability to adapt to changes. When built correctly, a parametric model can be easily changed by adjusting the set of parameters and constraints that govern its geometry. The model is then regenerated based on the new parameter configuration. This capability enables engineering change and model reusability, which in turn facilitates design reusability. However, CAD quality practices in industry are often overlooked, and modeling strategies (and thus the structure of many models) are far from efficient, which causes failures in the regeneration process as the model cannot react to changes adequately. As a result, 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.

This paper aims to lay the foundation for estimating the cost associated to parametric modeling changes. We provide an analysis of the different stages, decision points and relationships between the stages involved in the change process and present a roadmap for future research. We also propose some guidelines for the development of automated cost estimation mechanisms and describe application spaces for these tools.

The Parametric Modeling Process:
In a typical parametric feature-based modeling process, geometry is built by gradually combining a series of features in a specific sequence. These features are controlled by parameters (as they are built by sweeping parameterized profiles), and organized in parent-child relationships (because they are linked to each other by references, when a parent feature is changed its child features are updated accordingly [7]).

From a designer standpoint, many decisions must be made during the modeling process, as the robustness and flexibility of the model largely depend on how these features are connected and organized internally. For example, the two models shown in Fig. 1 represent the same geometry, but they react to changes differently because their internal structure depends on how they were built, as shown in Fig. 2. The notion that parametric modeling enables users to build “intelligence” into their models refers to the ability of the geometry to inherently represent design intent within its structure so that it can adapt to changes easily and effectively [6].

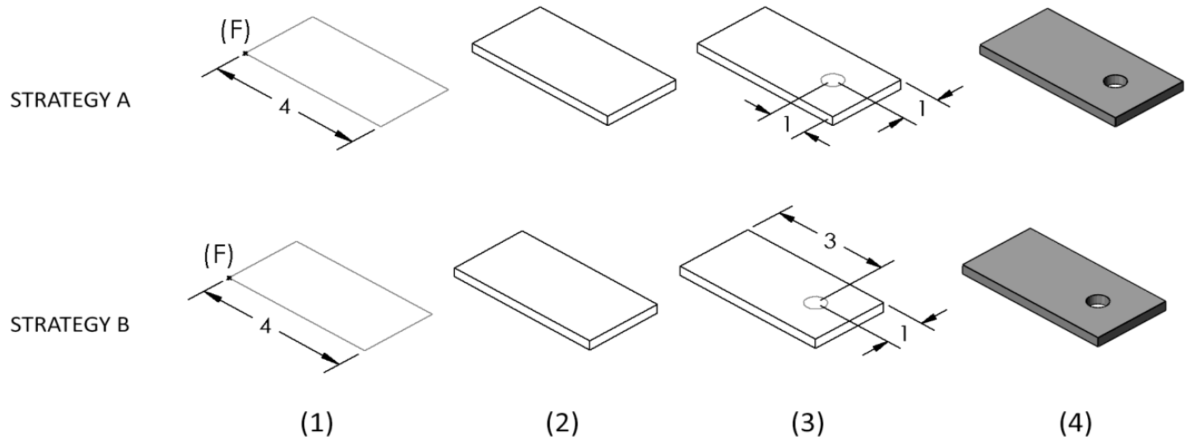


Fig. 1: Same geometry defined by two different constraining strategies. Size and orientation of the rectangle is defined, and Point F is fixed in space. Step (2) represents an extruded feature (controlled by the extrude direction and its length). Step (4) represents a cut (whose location is controlled in two different ways). Some constraints have been intentionally omitted for clarity [2].

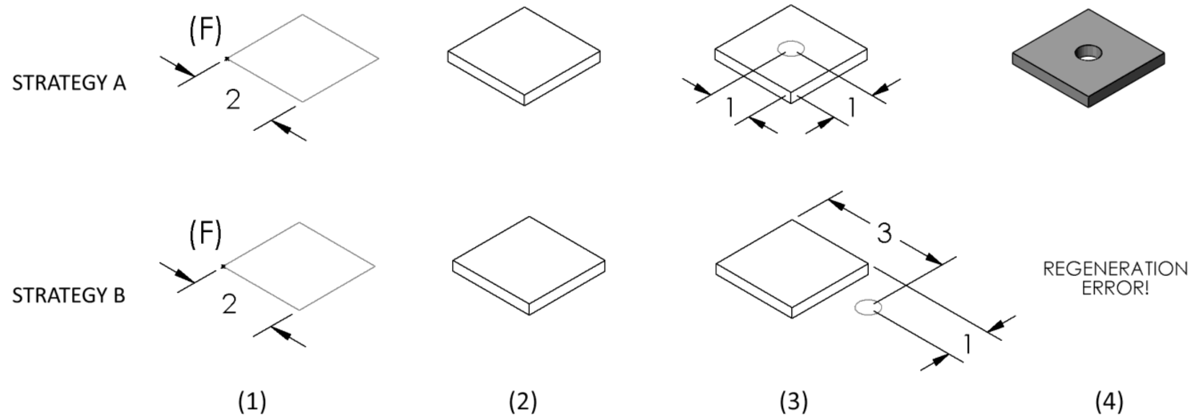


Fig. 2: Model from Fig. 1 undergoing a change process. Strategy A is successful. Strategy B causes a regeneration error as the cut (Step 3) does not intersect the model [2].

This paper presents a roadmap for studying change in parametric 3D models and estimating the cost associated to change processes. For the purposes of our study, cost is defined as a direct measure of productivity, primarily in terms of time and money saved in production. We justify the need for effective change practices and describe its relationship to CAD model quality (prioritizing reusability among other quality criteria, such as conveying design intent) as well as research strategies for tool development and evaluation.

*Change in Parametric Models*

Change can be defined as “an alteration made to parts, drawings or software that have already been released during the product design process and life cycle” [4]. A change may involve “any modification to the form, fit and/or function of the product as a whole or in part, and may alter the interactions and dependencies of the constituent elements of the product” [4].

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Engineering change is very common. Although most companies see it as a problem rather than an opportunity, engineering change provides for incremental product improvement [8]. In fact, effective change management strategies can quickly translate into significant competitive advantages for an organization.

In today's digital and model-based design environments, engineering changes typically encompass changes to the digital representation of the product. At the native CAD file level, these changes involve modifications to the various parameters and constraints that control the parametric solid model. Although some companies acknowledge the issues of working with low quality CAD models that are difficult to alter, most fail to estimate the time and money these issues represent. Part of the problem is the lack of mechanisms and tools to accurately assess the change process at the CAD level.

Investing in model and process technology (both initial creation and change) is critical for engineering companies to control the inherent high costs and risks of inefficient CAD models. In this context, it is essential to address engineering change effectively and holistically throughout the product lifecycle, including how it affects the digital model. For example, mechanisms to support the forward and backward traceability and quality of information are fundamental. In the forward direction, given a parametric CAD model, it is important to understand its internal structure, the manner in which the model was built, and the manner in which design intent was implemented. In the backward direction, we need to be able to obtain the design requirements or business rules to which a model, or a particular change performed to it, responds to. Traceability is the first step towards understanding the scope of the change, how the model will react to it, and estimating the related costs. In our view, several research questions need to be addressed, including:

- What patterns of change do parametric CAD models typically undergo? What are the most common ones?
- What kind and to what extent does a parametric model have to be able to anticipate and accommodate for changes? Is this a function of appropriate user training or expertise?
- At what point does rebuilding a model become more cost-effective than reusing it? What are the indicators?
- What information about the change needs to be explicitly captured?
- What are the requirements of a software tool to support and assess change?
- How can this tool be integrated with traditional systems, business processes, and users?

In this paper, change in a parametric model is examined from a user perspective as a series of iterative user actions that involve decisions and influence the geometry of the model. The methods and algorithms used by the geometric constraint solver of the CAD system to calculate the new geometry and regenerate the 3D model based on the new constraining conditions are not considered. For our purposes, in terms of cost, the time required to regenerate the model is negligible when compared to the actual modeling time spent by the user.

The evaluation of the quality of the change process is key to support the implementation of improvement strategies and any other decision-making activities related to modeling as well as the development of software mechanisms that can support them. In this context, there is a need for new metrics that can quantify the properties of the activities involved in the change process. For instance, how can we evaluate the complexity of a parametric model or the productivity of a CAD modeler? Likewise, empirical studies are needed to guide the evaluation of specific processes and specific industries as well as to increase our understanding of the principles and nature of CAD modeling. For example, simple indicators such as the frequency and severity of inefficient models received by CAD users in an organization, the percentage of models a CAD user rebuilds from scratch, or the total delays caused directly by an error in a parametric model can provide valuable insights on the quality and efficiency of an organization's CAD processes.

*The Change Process*

When a parametric CAD model is first built, a number of preventive measures can be implemented to increase its quality, in terms of flexibility and adaptability to changes. For example, the use of formal

CAD modeling methodologies [1],[5] and CAD quality practices [3] as well as compliance to company standards can significantly improve the parametric structure of the model and reduce the cost of performing a future change. However, not even the highest CAD quality practices can ensure a bulletproof model, as it is sometimes difficult to anticipate certain changes.

When a user performs a change and the CAD system attempts to regenerate the parametric model, two outcomes are possible: (a) the model regenerates successfully, or (b) the model fails to regenerate. This paper focuses on the costs associated to models that fail to regenerate (outcome b). Nevertheless, the fact that a model regenerates with no errors (outcome a) does not necessarily mean that it is correct. It means that the new constraining conditions and the corresponding equations are compatible and can be solved, but there is no guarantee that the design intent of the model will be preserved. For example, depending on the constraining strategy, a change in a particular constraint in the model may inadvertently affect other constraints without causing any incompatibilities or conflicts. These situations can be a significant source of problems, as users may incorrectly assume a model is correct based on the fact that it regenerated successfully and continue working and building new features on incorrect geometry. The cost associated to this outcome can be difficult to estimate but also substantial, particularly if the error is not identified early and the model is transferred to subsequent downstream processes.

When a model fails to regenerate (outcome b), the user has two alternatives: (b.1) attempt a recovery from the error, or (b.2.) rebuild the model from scratch or from a specific modeling step (e.g. the last safe step before the error occurred). The "attempt recovery" process can be described as iterative, where the user edits and rebuilds the model until all errors are eliminated or until he/she decides to rebuild the model. In any case, monitoring and understanding what happens during this iterative process is key to determining the cost involved in completing the change. A visual representation of the change process is shown in Fig. 3.

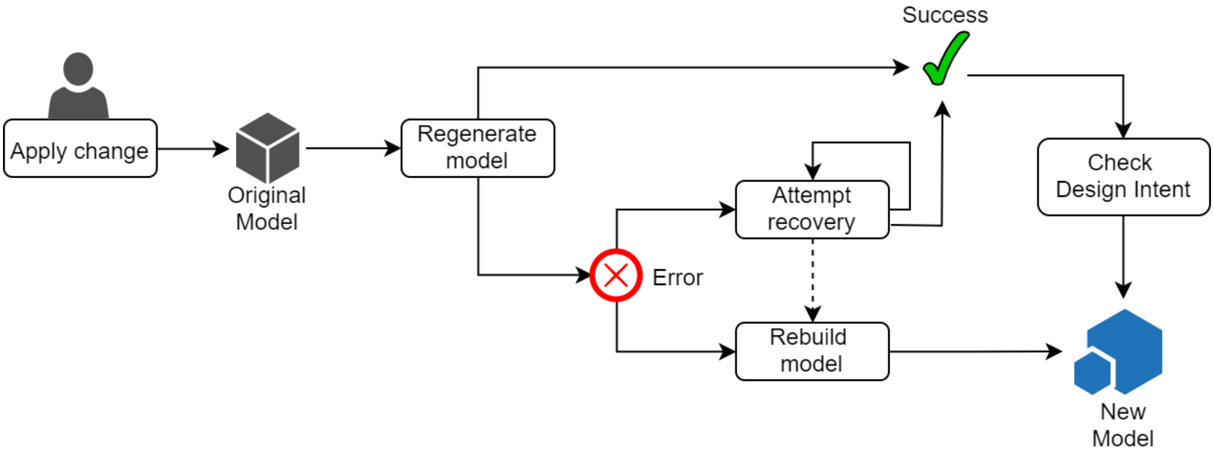


Fig. 3: Representation of the change process in a parametric model.

<u>Research Directions:</u>

The "attempt recovery" loop represents the actions that a user is performing to recover from a regeneration error. This is a critical piece of future research aimed at estimating the cost of change. Additionally, the model presented in this paper can be used to propose the following research directions:

- New metrics and software mechanisms are needed to track the user's actions and time spent in the "attempt recovery" loop as the model is undergoing change. These mechanisms should be unobtrusive (i.e., they should complement and integrate with existing design environments) and able to isolate actions related to change from regular modeling tasks. Similarly, determining the cost associated to situations that do not cause regeneration errors but fail to maintain the model's design intent should also be addressed.

- When studying the cost of change in parametric models, it is important to distinguish between perceived cost and real cost. Perceived cost refers to the cost or the time that a user or an organization thinks is spent performing a change. Real cost is the time that is actually spent completing the change. In this regard, there is a need for industrial case studies and field observations to determine how perceived cost compares to real cost. Furthermore, perceived cost is likely to be subjective and vary significantly from person to person. For example, a CAD user that is modeling on a regular basis and a project manager may provide very different answers when asked to estimate the cost of a change to a parametric model. These relationships, particularly when compared to real costs, can significantly influence an organization's decision to adopt new mechanisms and implement corrective measures.
- Given the strong connection between change and the CAD user, to what extent does the cost of changing a parametric model depend on the user's expertise? How can these metrics and tools be used to assess user performance and productivity? Data collected from change processes can be used to determine modeling habits (and malpractices) at an individual level and inform CAD training strategies both in academic and professional settings.
- The scope of change should be expanded to consider aspects such as the relationship between model comprehension, CAD quality and change (e.g., how difficult is it to alter high quality models that are complex and hard to understand versus changing low-quality models that are simple?) as well as quality degradation over time. How does the quality of the original model compare to the same model after multiple changes? This has practical implications, particularly when different users are involved in manipulating the model.

Conclusions:
Change management and reusability of the digital product model have a critical role to play in the future of CAD, as more companies transition to model-based engineering environments and the reliance on 3D models increases. This paper provides a roadmap for future research aimed at studying parametric modeling change from a process perspective to ultimately evaluate and estimate its cost. The notion of CAD quality and how it affects change and model reuse are generally neglected by academics and industry professionals. Our work proposes some lines of research that can lead to new tools and mechanisms for improving CAD practices and accelerating production.

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