The Cost of Change in Parametric Modeling: A Roadmap

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Abstract. In this paper, we lay the foundation for estimating the cost associated to parametric modeling changes and discuss its implications on the broader context of engineering change management. 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.

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1 INTRODUCTION

Engineering Change Management (ECM) plays a critical role in product development. When handled improperly, engineering changes can cause delays, overrun project budgets, increase the likelihood of future errors, and negatively impact the workforce, the customer, and the overall organization. Even the simplest of changes, such as modifying a dimension on a drawing, can have far reaching implications and drastic effects on many facets of development, their related systems and processes, and involve multiple stakeholders and teams at different stages of the product lifecycle.

In order to control the impact of engineering changes, many organizations implement formal engineering change management methodologies and procedures, which are typically supported by Product Lifecycle Management (PLM) technologies and computer tools. These strategies model change processes as a series of steps where changes must be requested, reviewed, documented, and approved before they are implemented. An important aspect of the change review process involves assessing the impact of a requested change, which requires the analysis of several areas such as the scope of the change (what other items will be affected?), the schedule (what will be the impact on the timing of scheduled items?), the cost of the change, and the domains that will be affected (manufacturing, supply chain, etc.), among others.

Many engineering changes involve modifications to the geometry of specific components and assemblies, which generally affect the digital representation of the product, more specifically the native CAD files of the design. Some researchers have developed methods to assess the impact of engineering change qualitatively [6], [20] as well as quantitatively, by analyzing the relationships between models and examining change propagation [14], [9-10], [12] to automate and document the identification of affected CAD models due to an engineering change [16], or by modeling risk as the product of change impact and change likelihood between components [5]. The links and interactions between the product component, the process and people involved in the change have also been studied [8].

In general, current methods that evaluate the effects of engineering change focus on assessing and, in some cases, minimizing the impact of change by analyzing models at the assembly level. However, many changes require geometric modifications of single parts, which may or may not trigger changes to other components. Even though most organizations, particularly the design engineers that are directly involved with CAD, acknowledge the value of working with models that are easy to alter, most fail to estimate the cost of working with poor quality models (i.e., models that are difficult to alter).

In this context, one of the most celebrated aspects of parametric feature-based 3D modeling is the ability to adapt to changes. When built correctly, a parametric model can be 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.

The goal of this article is to support the investigation of cost estimation and risk assessment in engineering change scenarios by providing (1) an examination of the factors that involve change at the level of parametric CAD modeling and (2) a roadmap of untapped areas for future research. The rest of this article is organized as follows. In section 2, we review the parametric modeling process and illustrate the importance of CAD quality when performing a change. Section 3 provides an analysis of the parametric change process. We describe the details and the connections to the future research avenues identified in section 4. General conclusions are discussed in section 5.

2 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 [18]).

From a designer standpoint, many decisions must be made during the modeling process, as a virtually unlimited number of strategies can be used to build the geometry. The robustness and flexibility of the model largely depend on how features are connected and organized internally. As a parametric model becomes more complex, its parent-child dependencies and their degree of interconnectedness also increase, which makes the model harder to maintain and the subsequent geometry modifications difficult to predict and execute.

For example, the two models shown in Figure 1 have the same geometry, but they react to changes differently because their internal structure depends on how they were built, as shown in Figure 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 [15].

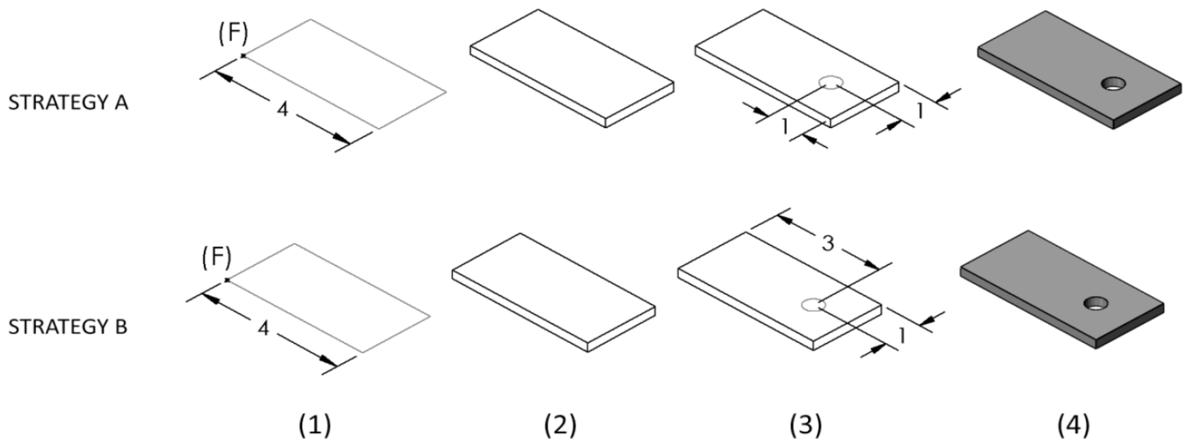

Figure 1: Same geometry defined by two different constraining strategies. Size and orientation of the rectangle is defined, and Point F is fixed in space. Step (2) represents an extruded feature (controlled by the extrude direction and its length). Step (4) represents a cut (whose location is controlled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

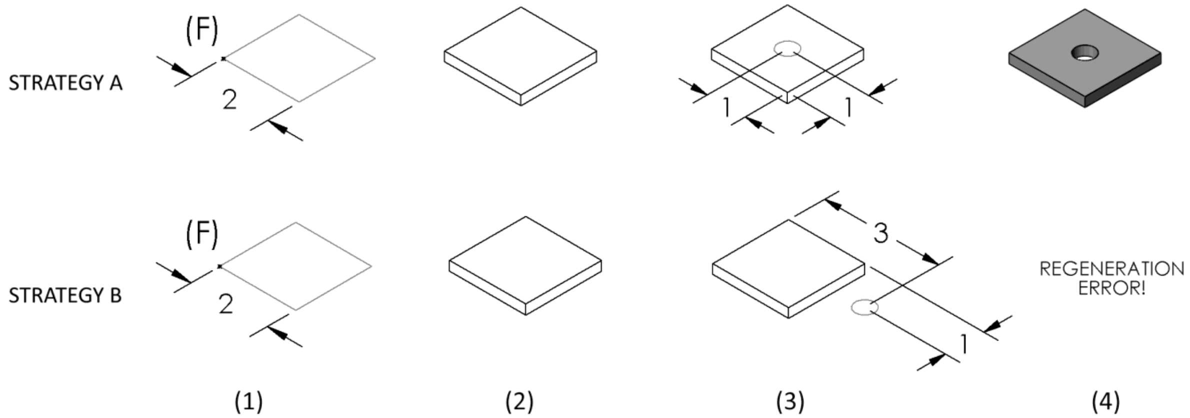

Figure 2: Model from Figure 1 undergoing a change process. Strategy A is successful. Strategy B causes a regeneration error as the cut (Step 3) does not intersect the model [4].

Research has shown that proper modeling strategies can significantly increase model quality and improve alteration time and reusability [3]. When used properly, CAD systems enable changes in the way products are developed [17]. However, poor modeling practices and dependency management typically result in models that are difficult to alter and require considerable amounts of rework. The exact impact on the overall lifecycle, however, is difficult to quantify and, although acknowledged, it is often relegated to the sidelines or even ignored when assessing the impact and risk of engineering changes.

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.

3 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" [11]. 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" [11].

Engineering change is very common. Change management refers to the strategies and techniques involved in identifying, analyzing, preparing, implementing, and validating change. Although most companies see it as a problem with considerable cost implications rather than an opportunity, engineering change provides for incremental product improvement [19]. 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. The impact of a native model on downstream models and processes, such as process plans, simulations, or NC programs, can be determined more accurately and managed more effectively when the native file is robust [2]. 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 or sequences 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 and business processes, and adopted by 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 must rebuild from scratch, or the total delays caused directly or indirectly by an error in a parametric model can provide valuable insights on the quality and efficiency of an organization's CAD processes.

3.1 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], [13] and CAD quality practices [7] 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 [3]. 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 easily occur if the model has sketches that are under-defined or poor design intent, as shown in Figures 3 and 4, and be a significant source of problems, particularly if the user performing the changes is not the original creator of the part and is not entirely familiar with how the part was built. 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.

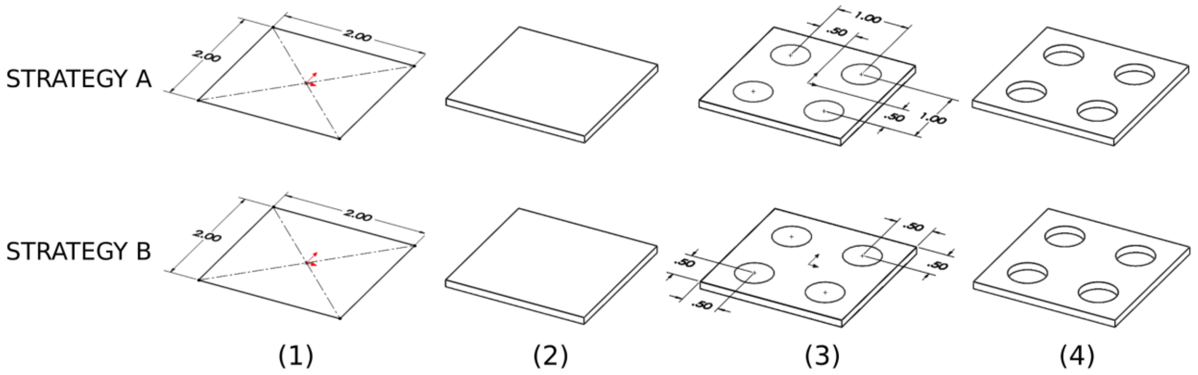

Figure 3: Same geometry defined by two different constraining strategies. (1) Size (2in x 2in) and orientation of the rectangle is defined with its center fixed at the origin. Step (2) represents an extruded feature (controlled by the extrude direction and its length). Step (3) represents the sketches of four holes (whose location is constrained from the origin in Strategy A and from the edge of the part in Strategy B). Some constraints have been intentionally omitted for clarity.

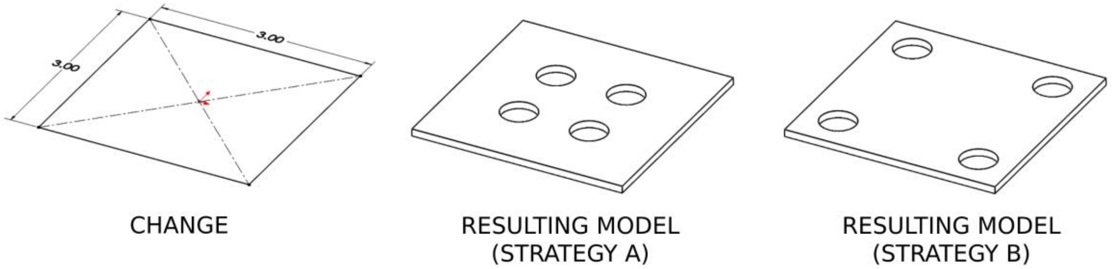

Figure 4: Example of a change (increasing the overall size of the square to 3in x 3in) that results in a valid model but causes loss of design intent. If the user is not aware of the behavior of the holes with respect to the dimensions of the rectangle, the model can inadvertently be considered "correct" as no regeneration error occurred.

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 Figure 5.

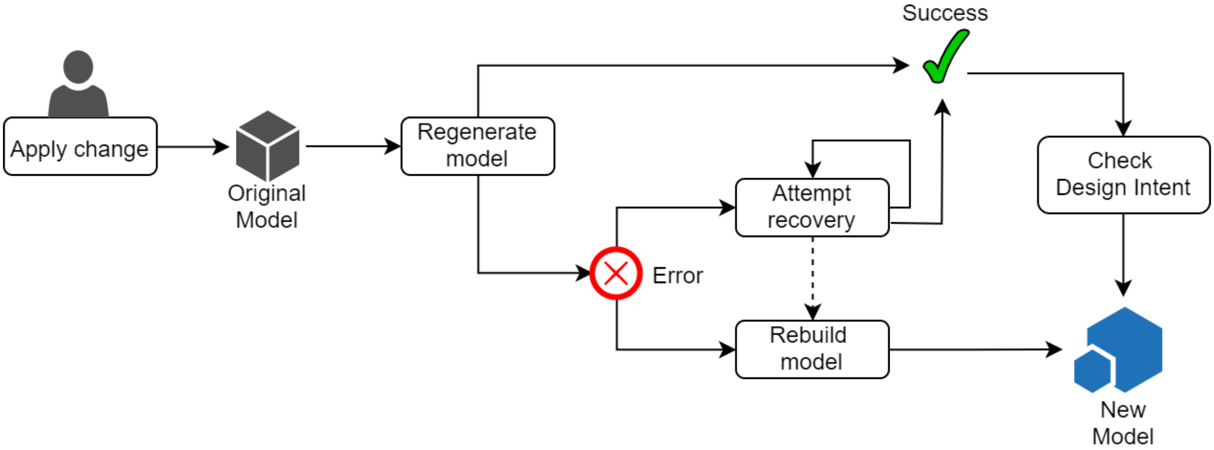

Figure 5: Representation of the change process in a parametric model.

The dashed line that connects the "Attempt recovery" and the "Rebuild model" stages represents a personal decision that a user would make after a certain number of failed attempts. The exact number will vary from user to user, as some individuals are inherently more persistent than others when it comes to completing these types of tasks. Additionally, the complexity of the CAD model as well as the user's experience and expertise will likely influence this decision. Ideally, the decision to rebuild vs. attempt recovery should be made as soon as possible, as the cost of all unsuccessful recovery attempts will be added to the total cost of rebuilding. In this regard, determining the point at which rebuilding a model becomes more cost-effective than reusing it becomes crucial. Finally, it is assumed that after a user decides to rebuild a model from scratch, the design intent will be properly integrated within the model.

4 RESEARCH DIRECTIONS

The "attempt recovery" loop represents the actions that a user is performing to recover from a regeneration error. This is a critical piece for 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. A general architecture for a software module that can be integrated into an existing CAD application is illustrated in Figure 6. When a regeneration error occurs in the CAD system, the module is triggered and begins to capture every user event, including keyboard and mouse events, specific events triggered by the CAD application, as well as the time when the event was triggered. After the model is regenerated successfully, the module can provide a snapshot of the actions that were performed to attempt to solve the error situation.

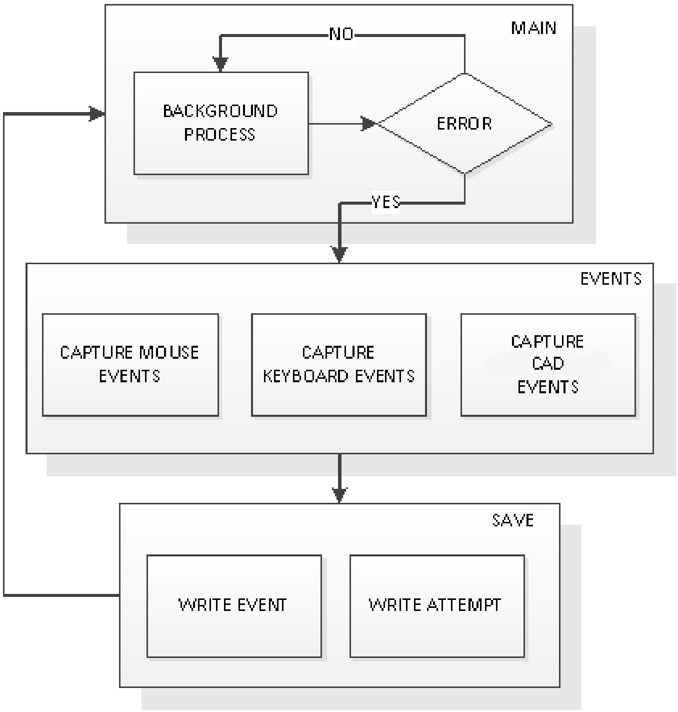

Figure 6: Functional block diagram of an architecture to track user's actions inside the "attempt recovery" loop.

- 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 the characteristics of the change (e.g., how difficult is it to alter high quality models that are complex and hard to understand versus altering 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 have been performed? This is particularly relevant when different users are involved in manipulating the model.
- Finally, the mechanisms and metrics proposed above can be used to compare modeling methodologies in a quantitative manner. By measuring the cost of changing a model, organizations can gather data on the effectiveness of specific modeling practices and weigh conclusions with more accuracy.

5 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.

Historically, impact analysis and risk assessment related to engineering change has been studied from a process perspective, ignoring the details of the digital product representation and its capacity for product improvement and reusability. This omission is unfortunate, as the factors that determine the cost of altering a CAD model can be considerable and are not generally understood. These matters should be of concern to all organizations that design and manufacture products.

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. In our study, cost is evaluated in terms of time to highlight the severity of the change management problem. Ultimately, it is necessary to determine the financial costs associated to these time costs.

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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