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OPTIMISATION OF PRODUCTS VERSUS OPTIMISATION OF PRODUCT PLATFORMS: AN ENGINEERING CHANGE MARGIN PERSPECTIVE

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1. Introduction

Engineering companies have to operate in the tension of two conflicting drivers: the optimisation of an individual product and the maximisation of standard components across a product platform. Both is driven by the objective to minimise cost, but applies on different scales. Optimisation largely aims to meet the requirements of a specific product in a way that minimises key objectives such as overall cost, weight, fuel efficiency, robustness etc. An optimised product ideally costs less to produce and less to run. Product platforms also aim to reduce cost and design effort for a product by standardising components across different products and product ranges. This leads to an inevitable tension. A fully optimised product would meet exactly its requirements and not exceed them. An optimised platform maximises communality and minimises cost, even if individual products based on the platform are overdesigned in some of their components. Components in a product platform need to be designed in such a way that they can contribute to meeting the requirements placed on all the products designed based on the platform. Product platforms can compensate to some extent by how the components are put together and by including alternatives for some components. This means that the products are unlikely to be optimal for their own requirements. Engineers balance this all the time by optimising the components they have control over and using the platform components they are given; in addition they can add to the platform and update it. Handling these trade-offs can be very hard, because designers do not know exactly by how much they are exceeding the requirements. For incremental products, the next generation designs are expected to be improved compared to the previous solutions – consequently leaving less room for flexibility. If the next generation introduces novel features, there is typically less experience of the design solutions and consequently it is more difficult to assess trade-offs. At the same time companies aim to carry over as many parts from the previous generation of the product as possible.

This paper argues that the key to balancing product optimisation and platform optimisation, or platform efficiency, lies in understanding the margins that components have with regards to different sets of requirements. This paper draws on eight interviews with ten engineers in a Swedish truck company and examples from the authors' industrial practise.

After a brief discussion of the research background in section 2, the paper will therefore introduce the concept of a margin in section 3. Our empirical example in section 4 draws attention to the fact that designers add margins to components for different reasons during product planning and product development, that are later used up in design changes. This illustrates the concept of product margins and the choices associated with it with an industrial example. Section 5 discusses different types of margins in the context of product platform before section 6 draws general conclusions.

2. Background

This research is addressing complex engineering products in the automotive and aerospace industry, which are designed incrementally to reduce cost, effort and risk. These industry sectors make extensive use of product platforms, which share components, systems and features across a range of products in a product family. This type of products are also subject to enormous variations around a core model to cater for the different needs to individual customers or market sectors, and therefore have to manage a complex portfolio of configuration and options that have to be brought together. At the same time many manufacturers are also selling products under a number of different brands, each having unique selling points. This has historically arisen through mergers or as a distinct strategy to reach a different market sector. To make brands economically viable it is however necessary to use product platforms across the different brands.

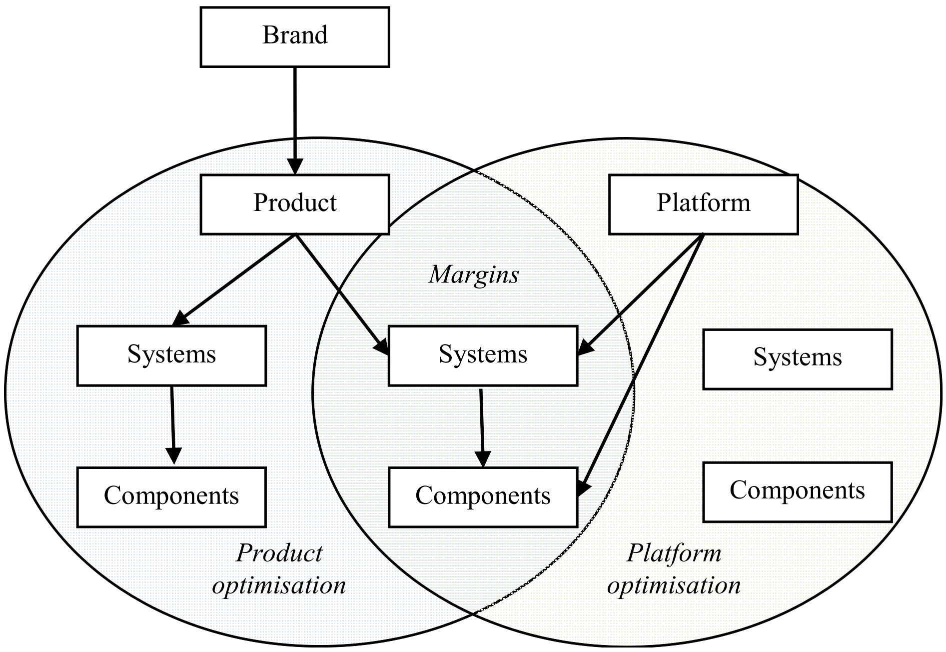

Figure 1. Relationship between product and platform optimisation

Figure 1 shows a simplified picture of the resulting relationships. Each product is sold under a specific brand, which might sell other similar products as well as totally different ones. The brand needs to maintain its distinctive brand identity. For example if a brand is known to be particularly reliable and safe, then this needs to be reflected in the products in a way that can be perceived by the customers. Each product is designed using as many elements of the platform as possible to minimise development cost and risk and might have components that are specifically designed for that product. This can be entire systems like engines or control systems, but also individual components. For example a company might aim to standardise a type of rivet across all types of products. Many companies also have different product families with are associated with different product platforms, for example a car company has super minis, small car, media car, family cars, sports cars etc., which share some components across all platforms, such as head lights, but others vary by size and requirements. Ulrich and Eppinger [1999] define a platform as a collection of assets, including components, processes, knowledge and resources shared by multiple products. Companies have interpreted this in two ways which hide different philosophies. A platform can be seen as the set of components and systems that are shared across all products in an organisation or the set of components that supports all the configurations of a specific product, some of which might be shared with all products in the organisation. For some classes of products, like engines or trucks, issues like size will prohibit sharing of components across different product families, so that the platform concept is extended to similar solution principles or technologies.
De Weck et al. [2003] point out that a company can pursue the following strategies:

- **No Leveraging,** where the platform is specific to market segment.
- **Vertical Leveraging,** where the platform is specific to the brand
- **Horizontal Leveraging,** where platform is shared across different brands for the product that operate in the same market sector
- **Beachhead Approach:** where one platform is shared across different market sectors and brands

Product optimisation is concentrating on an individual product. Shan and Wang [2010] point out in their review article on optimisation strategies that currently the "The most eminent challenges arise from high-dimensionality of problems, computationally-expensive analysis/simulation, and unknown function properties (i.e., black-box functions)". Considering multiple heterogeneous factors simultaneously is not only conceptually difficult, but also still computationally expensive. This makes mathematical optimisation across different products or platforms computationally difficult and very costly. Khire et al. [2008] are therefore proposing a combination of optimisation and solution visualisation to get the designers to guide and direct this optimisation process. This paper is however not looking at specific ways to optimise product design or platform design but to show these as two opposing drivers of design processes, which can only be resolved if the designers understand the margins that their components have.

The adaptability of a product to particular requirements is also discussed from the view point of the changeability, defined into an individual product at the beginning to allow for changes in the course of the product life cycle or during the design of the follow on model. Ross and Hastings [2005] define changeability as the a priori "degree of responsiveness (or adaptability) for any future change in a product design". Qureshi et al. [2006] and Martin and Ishii [2002] advocate assessing the flexibility of a product by systematically anticipating and rating the potential future changes to "future proof" the design, which will inevitable introduce a degree of redundancy into the product. De Neufville et al. [2006] introduces design options as a form of deliberate planning for a small number of potential changes that will be carried out to the product including calculations of the cost of planning in these options and the savings made in using a design option as opposed to making a change from scratch. Ross and Hastings [2005] advocate assessing the changeability of a system by mapping out the tradespace, i.e. the range of possible parameter values that provides potential solutions. Where the design sits within this tradespace defines the product margins. Research on engineering change addresses how a product definition or finished products responds to any kind of change and how organisations handle these processes. Eckert et al. [2004] identify the margins on individual components and therefore their ability to absorb and multiply change as a key factor in managing engineering change effectively.

3. Design margins

In Eckert et al. [2013] a design margin is defined as "*the extent to which a parameter value exceeds what it needs to meet its <u>functional</u> requirements regardless of the motivation for which the margin was included*". For example if a beam is required to carry a mass of 5 kg, but could in fact carry 7 kg than it has a margin of 2 kg. Most components and systems have to meet a multitude of different functional requirements. Some can be represented by single parameters; others will require a number of parameters, i.e. a parameter vector. However each parameter can also be subject to constraints and these are exceeded the design is no longer viable. For example if the beam is sitting in brackets at either end that can only carry 6 kg, the margins exceeds the constraints on the component, as illustrated in Figure 2. Two alternative component designs are drawn, each with different design parameters and constraints, yet with the same requirements. Each design will experience different margins, illustrated by the grey areas. The constraints are expressed through the dashed lines. Viable margined products sit within constraints.

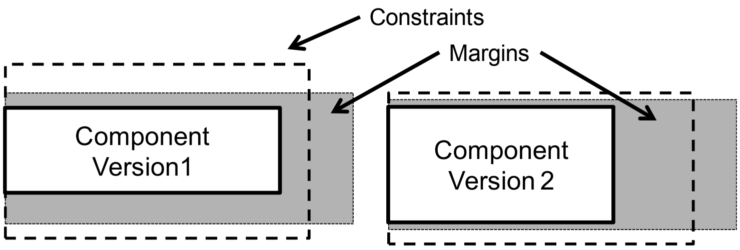

Figure 2. Requirements, margins and constraints for alternative component designs

Figure 3 illustrates that the component or subsystem of a product can be conceptualised along three dimensions: form (internal structure and configuration of features), function and material. By form we are referring both to external shape and internal (possibly micro-) structure. The component carries out a specified function in the product, which is usually described in terms of performance parameters and other target parameters reflecting the component's role in the product. For the third dimension, a component is constructed from a particular material or combination of materials with their own inherent properties. The combination of these three dimensions creates a working component, and the parameters arising from each of the three dimensions are required to describe the component. Parameters in each dimension have their own type of margin. Individual parameters can be traded off against each other across the three categories and margins allow this trade-off. The closer a component gets to its margins the less flexibility it has to absorb a change and make trade-offs.

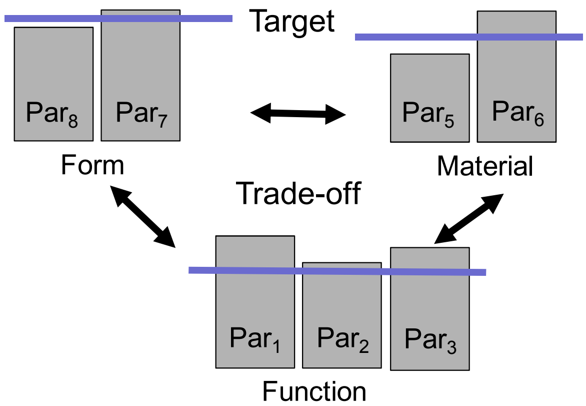

Figure 3. Trade-offs among form, function and material (see [Eckert et al. 2012])

Companies are often concerned with performance of components or products. In industrial practise the term performance or function can have a very loose meaning referring to anything that is not purely the geometric form of the product or component [Eckert 2013]. Another way to divide margins is into geometric margins and performance margins.

Margins do not only reside with individual components, but also apply to subsystems and systems in a way that is not deduced from the margins on specific parameters of individual components. These system margins on system parameters, allow changes in response to changes in other system parameters or in the operating conditions and uses of the product. The margins to absorb different operating conditions and uses do not relate to the margins of individual components in a linear and predictable way. For example a change in the ambient temperature in operation can require direct changes to the product, like the introduction of isolation material, but can also affect the behaviour of individual components, e.g. through heat expansion.

Changes can rarely be addressed in isolation and display complex interactions. For example a component might expand in the heat while at the same time the isolation material takes up some of the expansion space. The challenge lies in identifying these interlinking changes and managing them together in a coordinated way. A particular challenge arises when the same margins is affected by seemingly unconnected changes carried out in parallel.

4. Margins in industry

Companies are handling margins all the time in their design activity, but do not necessarily think of them as margins. Engineers are also often not aware of the margins components or systems have and therefore cannot reason with them systematically. In particular they are not aware of the reasons why their colleagues might have added margins to the product. This section presents the preliminary findings from interviews at Volvo Group Trucks Technology and an example of margins in truck configuration.

4.1 Methodology

Eight interviews were carried out with ten engineers in October 2013. The interviews lasted about one hour each. The interviewees were selected to cover different phases of the design process and different level of detail. They included

- Three design engineers
- Two virtual testing engineers
- One test engineer
- A specialist in mathematical optimisation
- Two product planners
- A product platform expert
- A tools and methods expert

The interviews were transcribed and then analysed, systematically extracting all quotes about margins and summaries of the related comments. This was then presented back to the interviewees and managers and discussed in a group workshop. The results from the workshop were included in a presentation and cross checked with two additional members of the project team.

Complementary responses were derived from a meeting with two subject matter expects at a consecutive visit to the company in December 2013. Following in depth analysis, the conclusions made were validated by a team of experts in a workshop in March 2014.

4.2 Product platform and versions

At Volvo, a truck is specified using so called *variants*, each of which belonging to a certain *variant family*. In order to specify a complete truck, around 500 variants are needed. Many of the variants describe physical alternatives, such as the size of the engine or the type of suspension, whereas others describe the environment in which the truck is designed to be used. The list of variants can be seen as the DNA-profile of the truck for which *links* then are used to specify the actual parts that the truck is composed of. For different reasons, all combinations of variants are not valid. In the product structure, this is documented with so called *restrictions*, each consisting of a combination of variants that are disallowed. There are, e.g., technical restrictions that the resulting parts would not fit geometrically, functional restrictions that the resulting product would not behave as desired, legislative restrictions that the resulting truck would not fulfil legal demands, or logical restrictions that the combination of variants makes no sense. There are also restrictions documented in order to limit the complexity of the product structure and the amount of engineering work needed, e.g., by limiting the allowed positions of an item for specific truck configurations. The company philosophy is to allow all configurations, i.e., by selecting of one variant in each variant family, unless there is a documented restriction explicitly forbidding the configuration. This leads to that there is a huge amount of possible trucks, and it is very few sold trucks that are unique with respect to their variant combination. For more information about the product structure, see Lindroth [2011]. Since there is such a large variety of trucks that can be ordered, a critical task for product development is to handle the great complexity, and to make sure that all orderable trucks will be built according to the intended design.

4.3 Margins across the design process

The interviewees were asked how they think about margins and how they handle margins in their daily life. They described margins very differently from their own perspectives as

- *Room for growth* induced product planning as a means to scale a solution or solution type for future applications. A simple example is connection points for electronic cables, where a new design might be launched with 12 connection points needing only 8 at the time.
- *Overdesign*, where a given design exceeds the current requirements, e.g. the brackets on a fuel tank could carry more weight than they do, which raises the question whether a bracket can be eliminated, if the tank becomes smaller or if diving in smoother conditions.
- *Redundancy,* which is used interchangeable with overdesign, but with a connotation of safety rather than cost.
- *Ability to absorb change* is discussed in the context designing new elements, e.g. a new suspension system, which has an effect on the surrounding systems.

In particular the design engineers talked about situations in which they needed to make use of margins, e.g. to accommodate an additional tank, in very concrete terms, e.g. "we looked for space under the cab" or the "the beam is strong enough", which is referring to underlying margins which are not explicitly specified. The platform includes solutions in incremental steps, e.g. the size of tanks changes by around 10 cm increments. The designers were thinking about the value of these increments as the margins in which they could accommodate other design changes. The design engineers concentrated on solving specific problems for specific models of trucks. The platform gave them constraints on their design problems which they could only affect selecting other components from the product platform. However, they were aware that the solutions that they have found might become part of the platform and therefore will be considered by other engineers. The actual value of the margins of many components was unknown to the designers or the organization, because they could only be revealed through testing. To test the product platform the company makes use of about 20 different benchmark configurations which cover both extreme and typical cases. The testing is set up to see whether the product passes given stringent tests, rather than to establish and measure at which point product failure does occurs. Product simulation would allow the company to establish these break point values, but to date they were not requested from the test engineers. However, while tests of the benchmark models could give the organisation a sense of the actual values, due to the computational complexity the actual values for all the configurations are unknown.

Product planning and to some extent brand identity in the case study company is though about in terms of what the company calls "features", which are high level characteristics of the product, such as safety, handling or fuel consumption, that is reflected in different way across the process. Components and systems often contribute to several features. The features are expressed in terms of requirements that the design needs to meet. The designers add additional product requirements and create a design that meets the requirements in the best possible way. In doing so they do not keep track at present of the margins that a particular design has with regards to each feature or requirement.

4.4 Truck configuration

One large area of complexity is in the wheelbase area of the truck where a number of items are competing for the same space. See Figure 4 for a rendering of a specific truck. The wheelbase of a truck is the space between the first driven front axle and the first driven rear axle. Along the truck chassis runs two frame rails on which the wheelbase items are attached with different brackets. The set of items that is to be positioned in the wheelbase area outside frame is highly varying between different customers, depending on market, legislative environment and transport mission. Examples of item types are fuel tanks, urea tanks, mufflers, battery boxes, air tanks, tool boxes, spare wheel carriers, wheel chocks and pneumatic distribution centres. For the particular truck in the figure, a fuel tank, a urea tank, a muffler and side underrun protections are packaged on the right-hand-side of the frame.

Figure 4. A screenshot from the CAD system for a particular truck

For many truck configurations, an important goal for the chassis packaging is to fit as much fuel as possible, given the set of items to be positioned. Therefore, at Volvo, there are around 40 different fuel tank dimensions available to choose between. Other features that have to be taken into account are, e.g., the weight distribution, the ground clearance, the fuel/urea ratio, the aesthetics, the resulting complexity of the routing of fuel lines and electric cables and the collective variation of the packaging for the whole set of orderable trucks. Clearly, if one had the problem of creating one single truck design, the result with respect to, e.g., amount of fuel, would be much better than when the complete platform has to be taken into account. However, in order to optimise the complete platform or set of configurations, one needs to constrain the design. This results in design margins, both for the designed parts to be packaged but also for the single chassis layouts. Decisions that have been, creating margins in some sense, include the following:

- Items are by default considered as rectangular blocks. Different design teams are allowed a rectangular design space in which to design their part. Clearly, this creates margins for the chassis layouts when different boxes are positioned after each other if the actual parts are not filling up the complete blocks. It also creates margins for the part design, where the parts can be redesigned within the box without direct influence on neighbouring parts.
- The holes on the frame rails at which to attach the brackets for the items are required to follow a fix grid with 50 mm horizontal spacing between possible holes. This results in margins for the single chassis layouts, since if the requirement were removed for a single chassis layout, its given items might be positioned closer to each other enabling a larger fuel tank.
- Fuel tanks are only available in fix sizes. The number of available sizes should be representing a reasonable trade-off between optimisation of single configurations and of the whole set of configurations.
- Fuel tanks are only positioned outside frame. In the space between the frame rails, there are a number of cross-members, whose positions differ between different configurations. There are also other items sometimes positioned such as air tanks and a unit for the parking cooler. Further, all pneumatic and electrical routing is located between the frame rails. If fuel tanks were allowed also between the frame rails, more fuel could be put on the single layouts. However, disallowing fuel tanks in the inside creates margins with respect to other variants since there will be space for various routing and crossmember solutions.

The fuel tanks are design in increments of around 10 cm. For other item types, there are just one or a few variants available with given sizes. Given a set of other items, the aim is often to find the largest fuel tank possible. To handle the variability, standard boxes are used by default, also for positioning, e.g., a spare wheel. For many specific trucks this means, that if the size of the items were treated in a greater detail and with less margins, the fuel tanks could be substantially larger.

5. Discussion

Margins can have different interpretation in different situations. In a company relying on a product platform strategy, where multiple versions of a product instance can be configured within the same product platform, the rationale is typically to satisfy the necessary variation of the end product with a limited set of combinations. Such product platforms aim to be cost efficient and make use of "economy of scale" thinking on an industrial scale. In this case the components might have considerable margins for many of the potential configurations. If changes are required to the component or components that might affect it and the margins cannot absorb it, the company either has to redesign the component or provide two options in the platform. If they add a new component, they have to check the compatibility with other potential options, which can require considerable effort.

We can think about margins on components and systems in three different ways, each of which needs to be understood for effectively managing both the product and the product platform

- Geometric margins, as in the example of the fuel tank, which are concerned with fitting different components into a limited space. A particularly tricky form of geometric margins are clearances and empty spaces, which arise from interplay of different component in a particular configuration. An understanding of them is urgently required when making design changes. While this is manageable for an isolated change, understanding clearance is a real challenge when multiple changes are occurring at the same time. Each change works from the existing product specification and therefore spots the potential, but might not be aware of others doing the same. Wanting to use the same geometric margins can generate unexpected links across otherwise unconnected systems. For example when urea tanks were introduced, space needed to be found for them in the wheel base. If the space is tight for short trucks, it is possible to place the urea tank into a hollow space under the cab; however this space is also used for cabling for the cab. This generates a link between urea tank and cab electronics which otherwise would not exist.
- Performance margins, which describe the components ability to meet its functional requirements under a given geometry and material. This can be very simple, like is the fuel tank big enough to meet the range requirements of the customers and the ability of a bean to carry additional weight. Often performance margins are complex and emergent in particular situations of use. For example whether the cooling system in an engine could withstand extreme temperatures in particular conditions of use. Performance margins need to be understood for particular configurations and particular situations of use. Performance margins can be tricky to assess, because groups of components carry out functions together and individual components carry often contribute to multiple functions, so that the component has different performance margins with regard to each function.
- Manufacturing margins associated with how the product is produced These can be associated with geometric margins or clearances, for example when a space needs to be assess to tighten a nut. However the interactions can be much more subtle. For example when two components are assembled and the tolerances of the combined component need to be assured and checked, which might be beyond the ability of existing manufacturing equipment.
- Maintenance margins associated with inspecting and maintaining the product, many of which are also concerned geometric margins and clearances, to provide access to components. Unlike with manufacturing margins, maintenance margins have to consider different conditions of use. For example while it might be possible to access a component with bare hands it could be difficult with mitten or when a multipurpose tool is used.

A more subtle, rationale for using a product platform strategy is their “role” to embody experience and product knowledge. A platform justifies putting considerable effort into the design of a particular component, which than might not need to be touched for a considerable lengths of time. Instead of needing to maintain a large team to continuously redesign a component or system, only a smaller team is required to check compatibility with the product platform and potentially update interfaces.
The build-up of knowledge of the product behaviour (the second rationale) reveals the opportunity to find optimal or stable regions of designs. This is particularly relevant for “integrated design solutions” where the functional behaviour of the product depend on how well functions are integrated. Such design solutions tend to be difficult to capture using combinatorial and discrete options. To achieve the correct function of a design the engineering typically require the use of physics based analysis. A simple example is the design of components with a fluid flow, or aerodynamic, function such as a fan blade. Components, and even systems, where the system behaviour and performance is dependent on the integral performance of the constituent components may require integrated analysis approaches to assess. The “degree of functional integration” increases the sensitivity due to components margins from a performance point of view. Often, dynamic vibration induced problems can escalate and cause symptoms in other places. A “poorly” defined bearing may result in vibrations that makes attachments for hoses and pipes to break somewhere else. A platform strategy can be helpful in representing “proven” design configurations.

6. Conclusions

It is fundamentally a strategic choice in an organisation how to balance optimal products with optimal product platforms. In balancing this multiple factors need to be traded off against each other: product production cost, product running cost and design effort. From a customer perspective this is a fundamental trade-off between purchasing cost and running cost. An optimal individual product might have the lowest running costs, but could have very high design costs and high production cost, because many components do not offer an economy of scale. However, putting together a comprehensive product platform can involve considerable effort in creating the platform, but also in maintaining it as all non-excluded combinations have to be checked as soon as the platform is modified. To meet strategic goals, like flexibility companies often invest considerable effort into providing a wide range of options, even if these so not necessary lead to a large volume in sales. Instead they might be motivated by brand image.
Understanding margins could be the key to providing flexibility into a product platform. Margins can be added in places where the volumes are low to maintain the breadth of offering without the effort of optimising configurations that are unlikely to sell. Understanding margins is likely to be needed to further allow product optimisation without compromising the platform strategy that has a direct relation to product cost.
In the ongoing research work, a clearer mathematical representation of margins associated to the product definition is being developed. Such formalism enables interaction with virtual design systems and is expected also to unify the terminology used in practice. The remaining challenge is how to develop an effective margins representation tool, with minimal additional effort for the engineers.

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