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THE ROLE OF DESIGN FREEZE IN PRODUCT DEVELOPMENT

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1. Introduction

"Freezes" play a major role during product development. Many companies use high-level stage-gateway processes for new product development (NPD), where freezes mark the end point of a development stage: for example, "specification freeze" defines the set of requirements the entire design will be based on, and "design freeze" describes the end point of the design phase at which a technical product description is handed over to production. However, academia seems to have paid little attention to freezes. While freezes are important to industry, only a few papers comment on freezes and describe their use, benefits and drawbacks.

Stage-gateway processes usually depict a single point for design freeze. However, some systems, parts, features or parameters need to be frozen prior to the official design freeze: dependencies between parameters require early definition and long lead time items need to be completed ahead of time [1]. A design sequence strongly influenced by freezes evolves. It allows structuring and planning of the design process and is a major benefit of freeze. This paper distinguishes between internal freezes that are the result of dependencies, and external freezes like lead times that are imposed on the design process. Both freeze types can apply to the product concept as a whole or to a particular detail.

An aim of freezes is also the reduction of the likelihood of further engineering changes [2-4]. For example, freezes avoid cost reductions that can be implemented in the next product generation. However, other changes like safety issues, problem corrections or new customer requests may still have to be included. Changes that need to be implemented after freeze may be more costly if tooling etc. is already in place. Quality control norms like ISO 9000 require a freeze point for change control to distinguish between the design phase and change implementation afterwards [2].

Product parts are rarely totally fluid until they are suddenly fixed at a freeze point. Parts are often "chilled", making changes less likely and more costly until the component reaches a point where it is only modified if the integrity of the product is jeopardised. A "chill" in this context signifies that the design of a part has been completed. When changes need to be carried out in a product architecture in which some parts have already been chilled or frozen, then a preferred implementation avoids changes to these parts. Unfortunately, the complexity and scale of dependencies between components often make it difficult to correctly predict the knock-on effects of changes that have been thought of as straight forward [5], leading to unforeseen changes to frozen parts. While methods have been developed in academia to assist in the assessment of the impact of a change request (for example, [6-8]), no known change tools take freezes into account.

The objective of the research reported in this paper is threefold: a) to demonstrate the importance of design freeze in product development, b) to give an overview of current handling of freezes in industry and c) to highlight the role of design freeze for change impact analysis. In the next section the paper briefly outlines the research methodology for this work. Section 3 gives a classification of freezes and defines the term. Section 4 comments of the handling of freezes in industry and the evolution of product parts during the design process. Section 5 describes the need for a change prediction tool that takes freezes into account. The paper concludes with a brief description of a freeze tool under development.

2. Method

To understand freezes during product design, the authors conducted more than twenty semi-structured interviews with design managers and designers in eight engineering companies in Germany and three companies in the UK. The UK companies were visited repeatedly while the German companies could only be visited once or twice. A UK manufacturer of diesel engines was the main source of information for this study. The visits to industry were backed up by an extensive search of literature on freeze and related topics.

The work forms part of an ongoing study on change prediction and process planning in complex design domains, involving interviews and observations with over 100 designers in the aerospace, automotive and textile industry (for more information and results of the study see [8-10]).

3. Design freezes

Although freezing the design seems to play an important role in industry, there is little academic literature on the topic. Some papers use terms like "design freeze" or "specification freeze" but hardly any paper defines these terms or describes the functions, benefits or drawbacks of freezes. This section gives a definition for design freeze and identifies advantages and disadvantages of freezes during the design process.

3.1 Definition of design freeze

The conducted industrial case studies have shown that freeze can apply to different parts of the design process. Figure 1 shows a typical stage-gateway process that can be found in similar forms in industry (for an overview of stage-gateway systems and other design process models see [11]). At least in theory the specifications are frozen before conceptual design begins, which in turn is frozen before detailed design starts. Before manufacturing can start the entire design needs to be frozen. However, reality is often far more fluid and processes can iterate across different stages. Freezes of the complete design or its details play a vital role throughout the entire design process, arising from within the company or coming from outside. Four freeze categories result that either address the product concept as a whole or part details in particular:

- **external conceptual freezes** arise from customer requirements or tooling constraints;
- **external detailed freezes** include detailed customer specifications, lead times and the use of pre-defined parts like platform parts, legacy parts or standard components that need to be incorporated into the design;
- **internal conceptual freezes** reflect the fundamental decisions made about the concept of the design throughout the iterative refinement of the product;

- **internal detailed freezes** occur when components, features or parameters of parts are frozen at any time throughout the design process; this typically occurs as a means of structuring the design process.

This paper focuses on detailed freezes affecting a parts or parameter during the detailed design phase. It includes both internal and external sources of freeze.

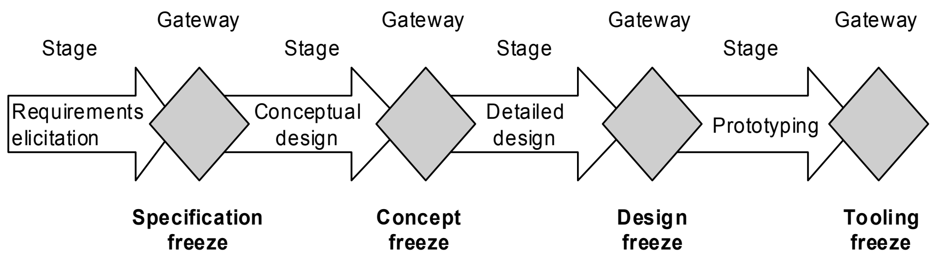

Figure 1. Different freezes in a stage-gateway process

In figure 1, the term "design freeze" refers to one point in time at the end of the detailed design phase at which the final version of the technical drawings is signed off and released to production [12]. However, it was already pointed out that different parts and parameters of a design need to be finalised earlier and at different times. Lead times for parts differ [1]. This paper extends the definition of design freeze to include any part or parameter of the product design that is defined during the design phase:

A design freeze is a binding decision that defines the whole product, its parts or parameters and allows the continuation of the design based on that decision.

Figure 2. Definition of freeze

3.2 Freezes in the product hierarchy

Freezes occur on three levels of detail:

- **Product freezes:** as was indicated, the term design freeze is most commonly used in the literature to describe the definition of the whole product design at once. It is a single point in time that marks the end of the design phase.
- **Part freezes:** these refer to single parts or groups of parts that are frozen at the same time ("system freeze"). A typical freeze of a group of parts is a "style freeze" in the automotive industry. By this point in time, the interior design of a car is frozen, and the shape and the available room for all parts in the passenger cabin has been defined. Of course, such a freeze is done in conjunction with the engineers responsible for the separate parts. Individual parts are frozen at different times to allow for design continuation of dependent components. Part freezes are frequently driven by lead time. For example, in one car interior design process the airbag was the longest lead time item and needed to be defined within a few months from starting work on the car, thus fixing many of the airbag's interface parameters. The benefits and drawbacks of part freezes are discussed in detail below.

- **Parameter freezes:** parts are not usually frozen at a single point in time. Instead, parameters, features and the interfaces to other parts are frozen individually before the whole part is approved. Key parameters that determine the performance, function and manufacturability of the whole part are usually set first. For example, while the material of a part may be decided early on to allow procurement, the exact part shape is only set later. Even the shape can be set in stages, as long as "metal-off" is possible, i.e. the part can be machined into its final form. Parameter freezes structure the design process. The dependency of key parameters sets a type of internal logic of the product, which governs process planning as well as decision ordering throughout the entire product. Without defining key parameters dependent decisions cannot be finalised.

This paper concentrates on part freezes during the detailed design stage, i.e. on the time between concept freeze and design freeze as indicated in Figure 1.

3.3 Reasons and benefits

The advantages of design freeze during product development are numerous: when the design is frozen, the product can be manufactured. When key parameters are frozen, dependent design can be finalised. For long lead time items, the lead time governs the point of part freeze. The design process can be structured by the freeze order of the parts. A design order based on part freezes evolves. It can be used for planning the detailed design phase and reducing the risk of rework. If the design process consists of many phases and tasks that overlap then freezes can set preliminary information as the basis for further work [13].

Once a part or parameter has been frozen, changes need to be carefully considered. A major application of freezes is the control and reduction of changes [3, 14]. As designers avoid changes to frozen parts and in particular to those that set key parameters, they have to find alternative ways to carry out the proposed change. These highly constrained changes can sometimes lead to very innovative solutions. However, sometimes it would pay company to weigh the cost of "unfreezing" an already frozen part against long chains of change propagation. Quality control norms like ISO 9000 also require the control of changes to the product after design completion [2]. Freezes have also been proposed as a means of increasing commitment by engineers; when they are forced to sign off frozen parts they assume direct responsibility for what has been signed [4].

4. Handling freezes

If freezes are understood as defining parts, then all product parts are frozen at some stage during the design process. This section discusses how freezes are handled in industry.

4.1 Use of freezes in industry

The freeze terminology was used in larger companies both in the UK and in Germany. Managers and designers referred to freeze and it featured in the official process documentation of some companies. The types most commonly referred to were "specification freeze", "concept freeze“ and "design freeze" although other elements of the design process were also referred to as frozen (for example, the decision on which options to install in a car – in German: "Ausstattungsfreeze", best translated as "configuration freeze"). The large companies that were visited in the automotive and aerospace industry all used high-level stage-gateway processes that indicated freeze points. Complex Gantt charts indicated the stages and milestones for most major systems that made up the design.

Official freezes were mainly found in companies with large design teams. Here, freezes were used to structure the design process, control changes and force the completion of design stages on time. Companies where a single designer was responsible for a product design did not refer explicitly to freezes. However, these companies also needed to finish the design process in time, had parameter dependencies and different part lead times. Hence, small companies also had to freeze. However, freezes did not need to be made explicit if a single engineer was responsible for all aspects of the design, could work out a feasible design order and keep track of part lead times. The single designer moved fluidly from one design phase into the next; the company companies did not need to use rigid stage-gateway processes to plan or structure the design work.

Freezes also have different "formality" levels describing how official and binding a freeze is. It has to be treated accordingly. For example, the major design freeze gateway with top management has a high level of formality: the product design has to be completed by this point in time. Freezes in official meetings are also a binding agreement between all attendants. Other freezes are less formal: designers can agree to a particular value and work with it until an updated value is required. While a parameter may be frozen, it may still be modifiable in negotiation with other designers even if it leads to rework.

4.2 Capturing the evolution of parts

Decision-based design views the design process as a sequence of decisions that define the product [15]. Product parts evolve with time, i.e. from a rough concept of the design to a technical drawing that describes the part in detail. Different parts evolve at different rates. Figure 3 indicates part lead times and design times that are the result of dependencies in the system. The figure gives a simplified view of a design sequence: iterations are not visible or planned for. Figure 3 shows that part design phases overlap: preliminary information can be used to start dependent part designs before an upstream part has been completed. Freezing some of this information and using it as a basis for further design reduces the risk of rework [16]. In the figure, the interface between parts A and B is frozen early so that the design of part B can start. The figure also shows part lead times: although part C depends on part B, it has a longer lead time and therefore needs to be frozen first.

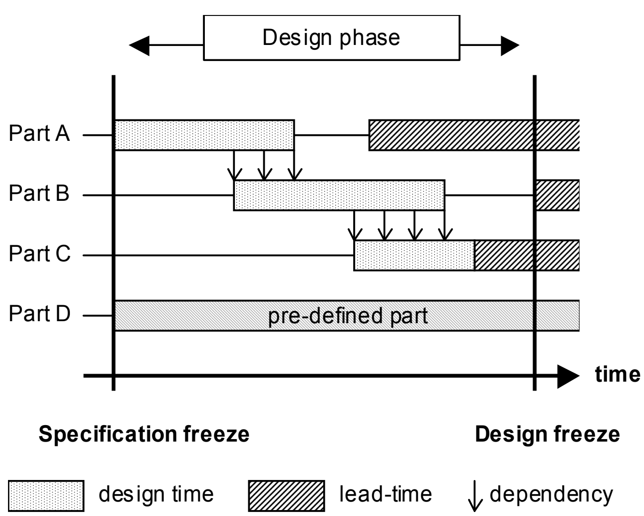

Figure 3. Part dependencies and lead times

Figure 3 also indicates the use of a pre-defined part. This may be a standard component that is bought in or a legacy part or platform part that is carried over from another product. The use of pre-defined parts gives a starting point for the design process, reduces the risk in performance and design and may lead to economies of scale [17]. It reduces the workload on the designer unless the effort in integrating the part is higher then the savings achieved by it. Pre-defined parts, such as off-the-shelve parts, are frozen externally and the designer only has limited influence on the design. While a standard part might be replaced by another, a change to a legacy or platform part has more severe consequences: the cost benefits of using a pre-defined part would be lost. Pre-defined parts can be considered frozen from the start of the design process.

The evolution of parts can be categorised into at least two states: before design freeze and after. The company that contributed most to the study, a British engine manufacturer, divided the part design process into further stages that indicated the degree of completion, and the designer's confidence, of the part. A part was called "chilled" when the engineer had completed the design and did not expect further modifications. It was called "frozen" when the technical drawings were handed over to manufacturing experts. This paper refers to different stages in the part design process as "freeze states": with each freeze state a part becomes more tightly defined. Figure 4 indicates four freeze states: at the beginning of the design phase, part C is unrestricted; a change has few consequences. As soon as the part design starts, the component is restricted and begins to constrain other parts. Parameters are defined throughout the part design process. Upon component completion, the design is chilled. It is frozen when the technical drawings are handed to production.

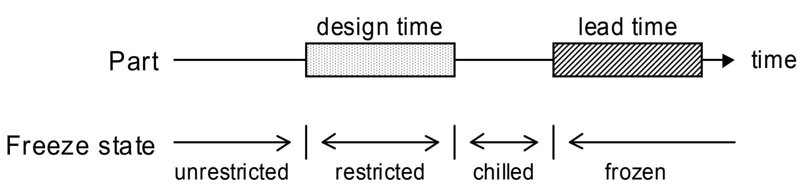

Figure 4. Freeze states during part design

4.3 Timing of freeze

The timing of freezes is often beyond the control of a company, as it is heavily dictated by lead times. Decisions that refer to key parameters of the entire system need to be make early to reduce the risk of rework, yet companies have some flexibility over when they freeze a part.

A number of papers comment on the best timing of freezes. Some papers recommend early design freeze and the incorporation of changes into future product generations [4]. Bhattacharya *et al.* argue against early freezes during new product development because it forces design teams into one design. This is dangerous for products in rapidly changing markets. A real-time definition process is proposed that freezes the design at a time that is market, customer and competitor dependent [18]. Similarly, Huchzermeier and Loch investigate the managerial trade-off between committing to a design without over-committing. High uncertainty generally increases the pay-off of late managerial commitment. It may therefore be worthwhile to postpone a design freeze if the exact product requirements are uncertain. The authors recommend regular formal reviews to obtain the necessary information, making design decisions where required and keeping parts flexible where changes are anticipated [19]. On the other hand, a study of 12 new product development time reduction techniques in the US electronics industry found no statistically significant correlation between freezes and development time [20].

5. Design freezes and engineering changes

A major application of design freezes is the control and reduction of engineering changes (EC) [2, 4]. To be able to cope with changes during design, the impact of a change should be well understood. Realising, and taking into account, the freeze state of all product parts is vital for change prediction.

5.1 Engineering changes

Engineering changes (EC) are a normal occurrence during the design process. Terwiesch and Loch define engineering changes as "changes to parts, drawings, or software that have already been released" [21]. Changes can be classified into two major sections: *emergent changes* that are caused within the design and *initiated changes* that are initiated by outside sources. However, the processes with which both types of change are carried out are the same [9].

The cost of an engineering change increases the later it is implemented. The "rule of ten" states that the cost of an EC increases by a factor of 10 for each succeeding phase in the design process [16]. For example, changes to the design in the conceptual design phase are generally a lot cheaper than changes in the production phase where tooling has to be adjusted and parts may have already been produced. A similar rule also applies within a single design phase: changes at the beginning of the detailed design phase are easier to implement and therefore cheaper than changes towards the end of the design phase. As parts progress from early freeze states at the beginning of detailed design into more binding ones towards the end, the impact of an EC on the part is likely to increase.

5.2 Tools for handling engineering changes

Different ways for coping with engineering changes exist. In the companies visited, procedures for handling change requests were usually in place, although they normally consisted of communicating change proposals to departments that were thought to be affected and receiving feedback about the impact and consequences for the part of the design that the department was responsible for. While some (but not all) of the companies visited stored change requests and their state of processing in a database, none of the companies used software tools to assist in the assessment of the impact of proposed changes.

A number of tools have been developed in academia to help with assessing the effects of an engineering change, for example C-FAR [6], Design for Variety [7] or the Change Prediction Method (CPM) [8]. A more detailed explanation of CPM is given below. However, none of these techniques takes into account the freeze status of parts or parameters.

5.3 Why freeze matters when predicting change impact

Change management procedures come into effect for modifications as soon as product parts are released. Because parts are finalised at different times for the reasons given above, change management is applicable even if not the whole product has been released. Unless a change prediction tool operates at a very high level of abstraction, greater accuracy of predication can be achieved, if the current freeze states of all product parts are taken into account. As was pointed out, the freeze state influences the ability of the part to accept changes and to allow change propagation. The freeze state gives a direct indication of the expected impact of a change.

It has been argued that a lack of overview by designers and managers is often the reason for insufficient understanding of likely change propagation paths [5]. For example, in one case designers were reducing the weight of a metal pipe but did not realise that the pipe was also used as a conductor of a sensor signal. The redesigned pipe met its objective of a lower weight but also caused the sensor to malfunction. The example demonstrates that even experienced managers and designers may not remember all component properties and the rationale for their selection. Similarly, it cannot be expected that managers and designers are always aware of the freeze states of all parts of the product architecture.

This paper proposes a freeze tool that captures the progression of part designs from "undefined" to "chilled" and "frozen" to give a broader design overview and allow for an investigation into engineering changes that takes part evolution into account. Such a tool not just uses aggregate values, but it indicates the change impact at all times during detailed design. Instead of having to carry out a detailed analysis whenever an engineering change is proposed, one tool with a dynamic representation of freeze states can be used at all times.

5.4 Target audience for a freeze tool

The target audience for the proposed tool are managers directly responsible for product parts or systems. These can be project managers if the product development is organised in projects, or they can be engineering managers in a functional hierarchy. These managers will normally be contacted if a change to parts under their control is proposed. They will also be part of any change review meetings. It is envisaged that the tool would be used to investigate change proposals. The benefits for the manager are threefold: the tool would provide an up-to-date indication of the freeze state of product parts that helps in assessing the progress of the design process, it would provide an indication of the change impact to be expected, and give a more objective way for justifying the selection of a particular change implementation.

Designers would benefit from such a tool if it allowed them to investigate the dependencies between parts and showed the freeze states of other parts. The designers could then base the part design that they are currently responsible for on parts that have already been frozen avoiding inadvertent requests for change. Inexperienced designers gain by observing design progression and the links to other parts.

5.5 Requirements for a freeze tool

The tool needs to meet two major requirements:

- to give an overview of the freeze states of the product parts and
- to indicate the impact of a change given the current freeze states of the product parts.

It should allow for the real-time updating of freeze states while also allowing the setting of freeze states for investigative "what-if" questions to inform design process planning. It should indicate pre-defined parts and treat these as frozen if required.

The effects of changes in part freeze states should be captured and directly influence the change behaviour of the part. The tool should be able to calculate the impact of a potential change based on the freeze states of the parts. When the freeze states change, so should the impact of an engineering change. The tool should allow the comparison of two or more change scenarios, for example for the same change implementation at different times or for different implementation at one time. Adequate visualisation of changes and freezes needs to provide an overview of current part freeze states, change paths and the impact of change propagation.

6. Towards a freeze tool

A tool that meets the requirements stated above is being devised based on the Change Prediction Method (CPM) developed by the Engineering Design Centre at the University of Cambridge, UK (for a full overview of CPM see [8-10]). CPM was designed to predict the risk of change propagation from one part of the product architecture to other parts. It has since then been extended to include different types of component links [10] and better visualisation of change propagation [22]. CPM allows an estimation of the impact of a change for a static set of likelihood and impact values. It does not take product evolution into account.

The freeze tool that is being proposed shares the underlying product model and change algorithm with CPM. It also allows the changing of freeze states for different parts, thereby manipulating the underlying set of static data. CPM is based on a definition of risk as the product of impact and likelihood. For every link between two parts, the impact and likelihood values for change propagation are elicited based on designers' experiences. A combined likelihood, impact and risk value is calculated based on direct paths and indirect paths between two components. The tool proposed here manipulates the direct impact and likelihood values to represent the effects of the freeze state on the part. Hence, change risk values differ for different freeze states.

A result of such a calculation of change risk can be seen in Figure 5 Here, likelihood and impact for a change to the fuel pump of a diesel engine are indicated. Two scenarios are compared: the crosses mark a change to the fuel pump at the beginning of the design process when most parts can be adjusted to absorb change. The points indicate a design state that was encountered in the company at the time of a company visit when four of twelve key components had been frozen. The underlying impact and likelihood values for the scenario including frozen components were changed by hand. As can be seen, freezing leads to a shift in impact and likelihood for most parts.

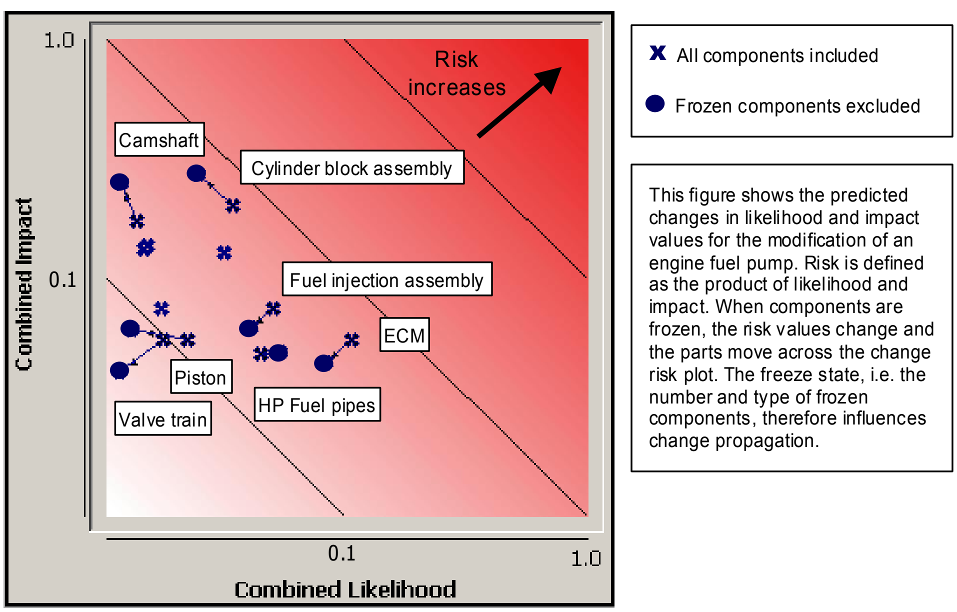

Figure 5. Change risk plot for a frozen / not frozen scenario

While the freeze tool is still under development and has not been validated, figure 5 indicates the potential usefulness of a freeze tool. A fully developed tool would allow the tracking of freezes with time and hence assist in the impact analysis of engineering changes. Different scenarios for change implementation could be investigated. Management gains from a better overview of freeze states and is better equipped to select the least risky change implementation in a specific time-dependent situation.

However, the research so far has already demonstrated a number of difficulties for the suggested tool. Estimating the impact and likelihood of change propagation for freeze states is difficult. It is not certain if the redistribution of likelihood and impact values could be automated. At the moment, this is done by hand but proves difficult and time-consuming. The number and effect of freeze states is also still under discussion. While this could be user dependent it also strongly influences the change impact results. Lastly, the exact tool requirements still have to be elicited from industry.

7. Conclusion

Although design freezes have not been comprehensively investigated in academic literature, they play an important role during product development in industry. Major benefits are the ability to structure the design process based on freezes and to control engineering changes to the product. Components evolve with time along a sequence of freeze states that indicate the likelihood and impact of changes to the parts at the time. Current change prediction tools do not take part evolution into account and can therefore only give a static image for change analysis. This paper proposes the development of a tool that gives a better overview of freeze state and product architecture and helps investigating the impact of changes dynamically.

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