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Optical quality as a product attribute – a descriptive study from the automotive industry

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Abstract
Geometrical variation, stemming from the manufacturing process, causes variation in the critical dimensions of an assembled product. The allowed product tolerances for these dimensions are determined in consideration of assembly, functional and aesthetic product requirements. The aesthetic requirements, that are of interest in this paper, are set to hinder visible geometrical deviations from having a negative effect on the customer's product experience in terms of aesthetic pleasure, attribution of meaning and emotional response [1]. It is therefore a judgment close to the sphere of industrial design. Consequences of visible deviations depend on the visual sensitivity to geometrical variation, which is the products tendency to reveal geometrical deviations when perceived though the human visual senses. Depending on product form and colours, the visual sensitivity of different split-lines, i.e. relationships between adjacent visible parts, will vary. Therefore it is difficult to specify generic aesthetic requirements on allowed variation. This paper is focused on how aesthetic requirements and visual sensitivity is handled in product development practice and presents the results from a case study at a Swedish car manufacturer. At the company, visible geometrical quality is handled as part of the product attribute, *optical quality*. The result is a description of rationale, problems & difficulties in how this specific product attribute is handled.

Keywords: Design Practice, Perceived Quality, Geometrical Variation

1. Introduction

When striving to control the effects of manufacturing variation on a product's critical dimensions, tolerances are assigned and geometrical robustness is strived for. Geometrical robustness is influenced by the locator positioning and the geometrical couplings in an assembly structure [2]. The main principle of robust design is to improve the quality of a product by eliminating the effect of the causes of variation without eliminating the causes [3]. The robustness principle can also be applied to product appearance, then referred to as visual robustness or as an opposite, visual sensitivity. The visual sensitivity of a product depends only on the product appearance which controls the visual consequences of deviations. Visual sensitivity can be studied on 4 levels*;* (1) the type of visual references built in between parts, such as continuity, parallelism or equal distances, (2) the optical prerequisites for visual detection of deviations, (3) human tendency to perceive them and (4) the aesthetic pleasure, attribution of meaning and emotional response related to perceived deviations [4]. Product experience connected to geometrical quality is often included in concepts such as;

Craftsmanship [5], *Perceived Quality*, *Optical Quality* or *Visual Quality Appearance* [6] all referring essentially to "The perception of quality experienced by a customer, based on sensory interaction and emotional impact**".** There lies however a difficulty both in literature and in practice to motivate why an issue such as geometrical quality would be more closely related to the customer's quality experience than other product aspects, such as ergonomics, exterior design or usability. One means of evaluating how geometrical deviations affect a product appearance is through non-nominal visualization. Nominal is here referring to the ideal product, with no variation, that only exists in theory. In [7] a tool based on a connection between a CAT (Computer Aided Tolerancing) software and a Virtual Reality software was presented. By use of this tool, geometrical quality can be visualized in a virtual environment at different phases in the product development process. By use of the tool, designers use their own perceptual senses to form a judgment of the visual sensitivity of split-lines. Little is however still known on how visible deviations affect the customer's product impression. Most certainly, specialists in the area have a trained way of visually inspecting a product, which may not represent what the customer perceives. In [8] it was suggested as fruitful to investigate the influence of manufacturing quality on consumer response to visual product form since it was pointed out that little work has been done in the area. An ideal is to create visually robust solutions in product areas where the risks for geometrical variation are high. This is however complicated by the fact that product appearance is determined by industrial designers early in the product development process while detailed knowledge on process variation often is gained at later stages. As tight tolerances generally are associated with high costs, it is important to make just decisions regarding what variation is acceptable. If this trade-off is not properly made early in product development, late and costly changes, either related to the manufacturing process, locator positioning or product appearance can follow.

2 Research approach

The background to this research is an aim to investigate whether the evaluation of visual sensitivity can be further enhanced by improved methods, tools, or further knowledge on customer response to visible geometrical deviations. The paper presents how visual sensitivity is managed at a company, in order to identify factors that influence the potential usefulness of further design support, as prescribed in [9]. The unit of analysis is the phenomenon of a products visual sensitivity within the context of the specific company. As the aim is not to draw extensive generalizations, but to shed light on a particular phenomenon in a setting, a flexible use of several research methods is chosen, as suggested by Robson [10]. The presented study (Figure 1) is a descriptive case study influenced by grounded theory [11] that was conducted at a Swedish car manufacturer. The company was selected due to the extensive specialization within the automotive industry, which had made optical quality emerge as an explicitly defined product attribute. Visual sensitivity had been defined as a concept through earlier research at the company [7], but the precise treatment of visual sensitivity in the product development process was not clear.

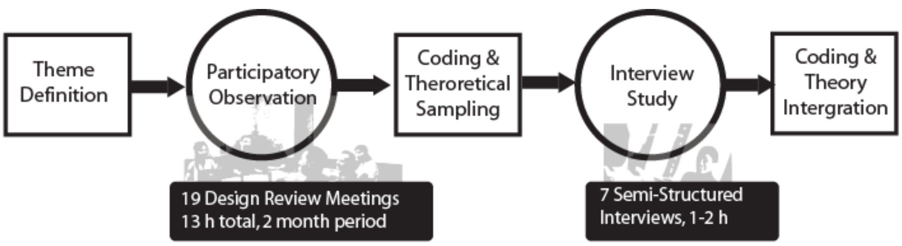

Figure 1. Methods used

The grounded theory principles of starting without strictly defined research questions and the ability to re-formulate the relevant questions and themes during the course of the study were considered appropriate for the study. An initial theme was instead formulated as; *how does the company manage visual sensitivity and what are the problems and difficulties encountered?* Participatory observation at design review meetings was the initial step since it allowed for a broad approach, not limited by terminology discrepancies and because it provided an opportunity for the researcher to gain comprehension of the project and setting. The sampled meetings were those where optical quality issues were treated and took place during a specific phase in the product development process (see figure 3, section 3.2). During coding, memo writing and constant comparison [11] was used to identify categories in terms of aspects of the product development work relevant to visual sensitivity and main issues for further sampling. This served as input to the following interview-study. Seven persons were interviewed; six engineers from the optical quality attribute group and one perceived quality attribute manager from the product planning department. The interview themes were (1) motivation of and background to the work done by the optical quality group, (2) how early can visual sensitivity be evaluated?, (3) handling requirements, (4) differences between types of OQ aspects (5) the trade-off situation, (6) use of methods & tools. Interviews were coded and reorganized to present the results in a coherent way.

3 Findings

In this section, the results from the study are presented. The presented headlines and sub-questions correlate to the final categories that were summarized as areas relevant to visual sensitivity.

3.1 Roles and responsibilities related to visual sensitivity

At the company, visual sensitivity is primarily addressed by the optical quality group, belonging to the perceived quality department, which is an attribute division under R&D. At the company, the different product attributes are handled by attribute groups. Their responsibilities are authoring, owning and promoting attribute requirements along with providing appropriate evaluation tools and defining verification methods. In each product development project, attributes are represented by a functional attribute analyst and system attribute analyst. Requirements are distributed to the vehicles different systems and components, for which the design engineers are responsible. The industrial design department initiates a product development project based on an order from product planning. They define the products visual sensitivity, as they create the product appearance. Through setting requirements and providing feedback to industrial design, the optical quality group is to ensure that the design intent will not be distorted due to geometrical variation, which includes evaluation of visual sensitivity. Predictions of the assembled products tolerance distributions on critical measures, provided by the geometry system developers, serve as important input to this task. While the attribute group belongs to R&D, a subgroup within testing and one within audit independently evaluate the same product aspects.

A tendency within product development is that industrial designers are allowed to motivate their solutions through personal judgment, while engineering designers are to motivate solutions though physical measures [12]. When judging appearance, a holistic approach is required and a certain freedom is often fought for by industrial designers to avoid the obligation to technically motivate solutions when it comes to detailed geometrical features.
Here, the optical quality engineers have a sort of opinion mandate, allocated outside the industrial design department, to use their personal professional judgment to decide what a solution or geometrical deviation would look like in the eyes of a customer.

Optical quality product aspects
Optical quality as a product attribute includes *geometrical quality* and *appearance quality*. Geometrical quality comprises the effects of visible geometrical deviations. These are controlled by specifying allowed variation in the flush and gap measuring directions, parallelism measures and nominal gap sizes (Figure 2). Appearance quality is about avoiding unsightly elements such as screws, weld-points, rat holes and ball corners that are not supposed to be visible on and assembled car. See-through effects, i.e. when underlying features are visible through the split-lines between adjacent parts, are appearance quality aspects that appear both on nominal and non-nominal geometries and provide a connection between appearance quality and geometrical quality aspects. When placing the split-lines, they are used as form elements that accentuate the overall form, which makes it, along with assigning nominal flush values, the responsibility of industrial design.

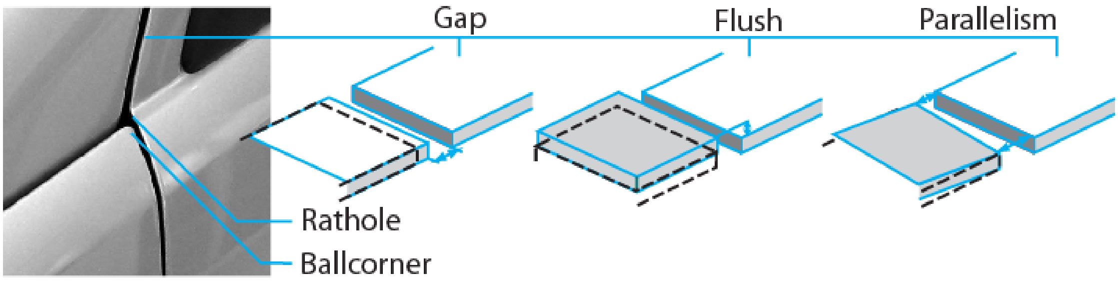

Figure 2. Optical quality aspects

Benefits of handling of optical quality as a product attribute
The respondents' views of the benefits of handling these appearance-related aspects as an attribute instead of as sub-division within industrial design, which had been tried earlier, were;

- The group could provide competence on tolerancing and geometrical variation.
- The network including organizational and competence related proximity to the geometry system developers was an advantage.
- Attribute groups had the opportunity to follow up an area throughout the product development process and to ensure that established knowledge was shared between projects. They kept track of competitors and formulated long-term strategies to enhance performance within the area.

A cultural difference was also mentioned, where industrial designers were considered to live in a nominal world, not involved in what cars looked like in the factory. It was likely that industrial design were to have opinions on the optical quality requirements, especially if they were to result in appearance-related changes, but they did not have the right to change the requirements. The collaboration with industrial design was however regarded as well functioning. One participant experienced that when optical quality was an attribute, people respected the area more then when it was a sub-division within industrial design.

Views on the relevance of optical quality
A summary of the participant's views on the importance of optical quality was that the car was to give a solid impression, look well built and worked through. A continuous work to define the relevance for customers was however part of the job, where it was experienced as difficult to provide any good directives. During clinics or audits, customers had difficulties understanding the aspect. Instructing them to look at the focused aspects meant educating

them and making them see things they not might otherwise have seen. A match between the groups own judgment, and the general rankings in the area in more broadly formulated customer surveys had however been found. In addition, motor journalists often commented on the area.

3.2 Optical quality in the product development process

Here, the main optical quality tasks in the product development process will be described (Figure 2). Andersson [13] considers the approach to requirements management at the specific company as close to systems engineering, as defined by Stevens et.al. [14]. The breakdown of product requirements at the company starts with business and user requirements and ends in component requirements, via complete vehicle and systems requirements [13]. The product development process used at the company is based on a number of milestones indicating that a predefined set of requirements are to be fulfilled by the project, to ensure that it is progressing according to plan. Further descriptions of the requirements process at the company is provided in [15].

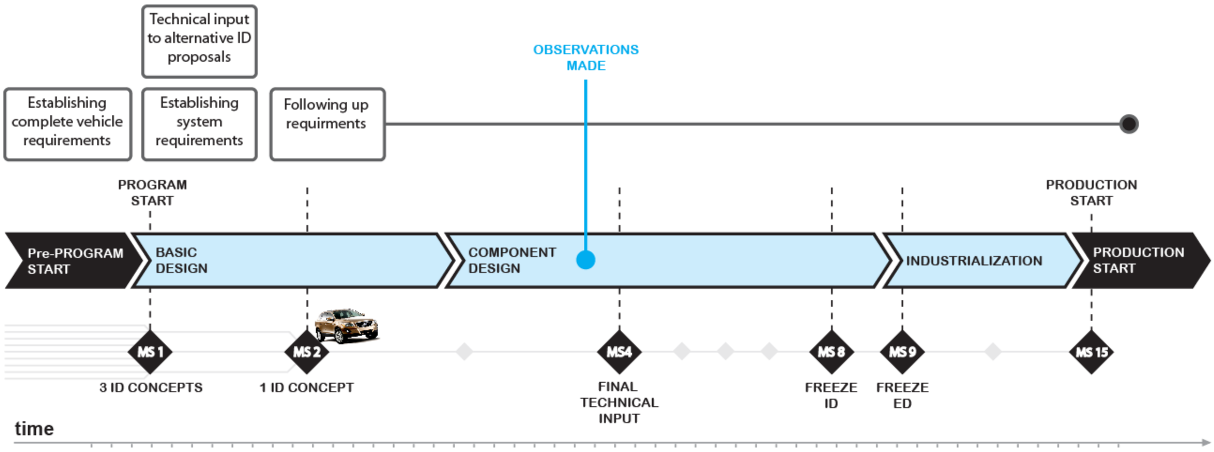

Figure 3. Main optical quality activities in a product development project

Establishing complete vehicle requirements

Before official programme start, complete vehicle requirements are formulated, that are to be solution independent, but measurable by means of a specified method. They are not yet formulated as product tolerances. This is based on input on user requirements from the product planning department, including defined goals in terms of desired rankings in a competitive set of specified car models. Interviewees involved at this stage considered it important, during product planning and when setting complete vehicle requirements, to match optical quality strategy with industrial design strategy. If optical quality is considered to be valuable for the sought target group of a car model, applying industrial design concepts that are known to be visually sensitive and geometrically difficult to achieve, would involve risks.

Technical input to alternative industrial design proposals

As an important step in identifying required appearance changes early, technical input is provided to competing industrial design proposals, before system requirements are set. Although interview persons did not believe optical quality to be a central criterion for the selection of a concept, industrial design themes could be limited and project members could be warned that for a specific industrial design concept, the subsequent level of requirements would be high. The placement of split-lines could also be slightly changed. Pressure could be set to improve the technical solution in the area and potential problems could be identified or solved early in the project. The most important aspects controlling at what point feedback could be given were that;

- Interfaces between parts needed to be defined. Industrial design models were often surface models, where split-line positions could be more or less clearly indicated.
- A certain level of maturity was required. Feedback was not interesting at the point where industrial design proposals were just "free artistry". If feedback from areas such as body engineering or sheet metal stamping had been provided and incorporated into the proposals, the relevance of optical quality evaluation increased.

The evaluation was primarily based on;

- The ability to see a few steps ahead and foresee how a solution would evolve related to various requirements and prerequisites and how that would affect optical quality.
- Knowledge from earlier projects regarding which car areas suffered a risk for large variation. Some types of relations between parts were avoided because the attribute analysts knew that historically, there have been problems achieving a good result.

Visual sensitivity was evaluated at this stage, but mainly in combination with the prerequisites for achieving small variation. An evaluation with focus set exclusively on visual sensitivity, did in other words not take place. Potential problems were sought for and there was little use identifying visually sensitive solutions where the expected output variation was low. Although early feedback was provided, new issues would also emerge as a product matured. Appearance quality aspects were for instance dependent on information such as the detailed geometry of underlying parts.

Establishing system requirements

When complete vehicle requirements are broken down into system requirements, nominal gap and flush values are assigned as well as the magnitude of the allowed tolerances, referred to as the requirements level. A high requirements level means small product tolerances. In this step, visual sensitivity was assessed in terms of what output variation could be allowed. When setting system requirements;

- They were based on the order from product planning along with the complete vehicle requirements which clarified how the car should perform in relation to competitors. Estimations of the flush and gap values on the competitive set were therefore made.
- The relations between parts on which requirements were set could be generic, and were included in a master document. The values should however ideally be based on what was suitable for the specific appearance.
- The requirements sometimes had to be based on process capability.
- Earlier decisions on requirements, from other car projects had an impact on current one, as this would function as a reference point in the following trade-off between requirements.

Obtaining precision in the connection between the product planning order, complete vehicle requirements and the system requirements appeared to be intricate, as often described when it comes to the connection between functional and numeric requirements. Though the preferred rankings in the competitive set constituted a frame of reference for breaking down the requirements, it was mentioned that the system requirements were the core activity, and that the other documents were more or less derived from them.

Mediating between industrial design and manufacturing was described as part of the role of the optical quality engineers. Setting system requirements was however still difficult when there was an apparent collision between manufacturing or engineering design prerequisites and the requirements level assessed as necessary for the product appearance. Some different attitudes towards this situation could be outlined. The ideal for the activity was described as; *"Requirements should reflect what the market looks like. A good requirement is something that makes it look better for the customer."* On the other hand it was stated that; *"The project members will laugh at us, if we set a tight requirement, that we all know that there are no prerequisites for".* Determining when to strive for improvement and when to accept he project prerequisites was an important judgement

Another important function of establishing system requirement was to set priorities, for instance to allow one corner of a part to vary more than the other corners. The requirements were to show geometry system developers the optical quality priorities. Another observation was that it appeared to be rare to lower the requirements if the visual sensitivity was assessed as low, instead there was no attempt to strive for improvement.

Following up requirements

Changes in requirements are often made when requirements are found to be conflicting [13]. Requirements are balanced, which means their levels are adjusted. The necessary trade-offs related to balancing requirements to each other and to costs are ultimately made by project managers. At the company, it was observed that gaining comprehension and a will to meet optical quality requirements amongst other project members was an important assignment for the optical quality engineers. Their efforts in following up the status of their requirements meant participating at design review meetings and promoting the fulfilment of the requirements in a collaborative setting. Finding connections and allying themselves with persons representing other attributes to promote the requirements was mentioned as important as well as finding a good balance between stating ownership of requirements and making others feel invited to comment on them. At the meetings, both whether an optical quality aspect would be visible to the bare eye and whether it was relevant for the customer was at several points questioned. For instance, the desired target group of the car was discussed related to a cost driving decision that would enhance appearance quality. It was unclear how to value the aspect in relation to the target expression of the car. Certain characteristics of the requirements lead to extensive discussions or unclear aims. The statistical nature of the requirements appeared to weaken the motivation to meet them. As cited from a design engineer, *"If it happens once in 2000 cars, how important is this?"* Discussions were also raised when the fuzzy aspects related to customer perception were translated into precise and clear numeric requirements. Requirements could be motivated by optical quality by arguing that things should not be "to big", "too prominent" or "too sharp", but the exact values remained hard to motivate.

The interviewees believed that the attitude towards optical quality was dependent on the experience and attitude of the person they were dealing with. It was pointed out that when the requirements meant additional work for the design engineers, they questioned them instead of improving the product. The optical quality attribute analysts were to educate other project members on optical quality aspects. This could involve making them consider; what the eye sees though materials with different optical properties, the worst case statistical outcome not only nominal gap or flush values and variation in all degrees of freedom.
They had to bring forth that the current product appearance made it unsuitable to base a decision on a similar decision in an earlier project, despite commonality in the technical solution and they had to motivate why certain areas were prioritized over others.

An ongoing competition between attributes to promote their aspects was described. Some product attributes were more precisely measurable than others or had more powerful evaluation methods or simulation tools. Optical quality experienced a continuous need to give evidence that the car could be better in their aspect, to conduct promotion activities at different levels on the company. There was also a need for a common view on priorities within the group in order gain credibility.

Verification and validation of requirements

As defined in [14] verification involves checking a product against its requirements while validation aims to ensure that the product meets user requirements in the operational environment. Optical quality requirements are formally verified by measurements on manufactured cars. Requirements on nominal gap and flush values were in effect directed towards the project engineers and could be verified by measurements in the digital models. Requirements that could not be measured, such as certain appearance requirements, were sometimes set to be used as input for design engineers. Assurance that the right requirements had been set, i.e. validation, was described as difficult to provide. Customers did not complain on geometry and appearance quality, problems were not reported during surveys with car buyer and user clinics were difficult to perform. If there had been failure in setting system level requirements on a critical relation, this could be discovered during industrialization or production. However identifying unnecessary requirements or requirements where the allowed tolerance was to tight, i.e. relations that did not reflect user requirements was more intricate.

General aspects of the requirements process

Some additional remarks regarding the requirements process are that;

- The breaking down of system requirements to component requirements was the responsibility of geometry systems developers and not an optical quality task.
- It was not clear amongst participants whether the attribute analysts were to provide alternative design solutions, when choosing to set a requirement that would need a design change in order to be fulfilled. Formally they were not supposed to, but in practice they were expected to.
- It was stated that in ongoing car projects, little could often be improved regarding the attribute, due to commonality plans and the use of pre-defined manufacturing process solutions. A large part of the effective work of the group therefore took place in long-term development projects, such as platform work or research oriented improvement projects.

3.3 Tools and methods used

The main tools during the process were the non-nominal visualization tool along with nominal digital models and a customer field of view functionality [16]. However for evaluating nominal see through, CAD models were sufficient. Among attributes, the group considered themselves to require high CAD maturity since surfaces and details needed to be detailed and correct. In product development projects, useful input to decision making was gained by looking at earlier car models with similar visible relationships between parts that were preferably built on the same platform. The function of the non-nominal visualization tool can be summarized as;

- The most important function of the tool was not for the optical quality group to understand that there was a problem but to show others that there would be a problem.
- Due to differences between real life visual perception and perception in virtual environments, they tried to avoid assessing the appropriate requirements level by use of the tool. At some points it was however used to make judgments, for instance regarding

allowed non-parallelism. This often occurred when a new solution, not encountered before, was introduced.

- The colours of parts visualized by the tool were adjusted so that they were clearly visible on projection screens in order to provide clear information on meetings and not to evaluate how different colours made geometrical deviations appear in realistic environments.
- At points, using the tool was experienced as time consuming, especially when incompleteness in digital models was discovered when setting up the visualizations.

4 Discussion and conclusions

A conclusion from this study is that to a large extent this automotive company has a clear frame of reference when defining requirements on allowed output variation. Cars are such conventional products, that the relationships between the exterior parts are very similar on different models. This allows for reuse of knowledge and judgments when making a new car as well as competitor analysis on a detailed numeric level. As a conclusion, the situation at the company does presumably not correspond to that for other less mature products. On the other hand, this maturity makes it unlikely that other industries would display a more developed approach to optical quality or visual sensitivity.

The relevance of addressing visual sensitivity in product development, as represented by this company, depends on a number of conditions. There needs to be a risk for geometrical variation, and there needs to be a realistic possibility of decreasing this risk or to change the product appearance. Visual sensitivity is therefore relevant at various stages throughout the product development process, but not often exclusively addressed. Visual sensitivity is however in focus when setting priorities with requirements and attaining a common view within a group on what aspects to promote the most.

The impression from the study is that it was that the strategy of the optical quality engineers to make the requirements level as high as possible in every project. An interesting topic is what types of cars, in terms of intended product expression and target group that could support a lower optical quality requirements level. However, as observed, the in-built dynamics between attribute groups makes it necessary to strongly promote the importance of an attribute in order for it to have an impact within the car projects. In this competitive context, further means to promote the attribute would presumably be experienced as useful by the optical quality group, for instance through enhanced ways of measuring visual sensitivity or by quantifying the overall optical quality performance level. It has been shown that the non-nominal visualization tool primarily was used for visual communication during meetings. Since visual sensitivity was continuously discussed at meetings, it is plausible that further knowledge in the area would also provide some meaningful input to decision making and to the necessary trade-offs between attributes.

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