

# **INTERPLAY OF INDUSTRIAL DESIGN AND ENGINEERING DESIGN INTERPLAY: AN EMPIRICAL STUDY ON TOLERANCE MANAGEMENT IN THE AUTOMOTIVE INDUSTRY**

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## **1. Introduction**

Conflicting viewpoints on product development work, due to factors such as differing knowledge and diverse backgrounds, often result in poor integration of the industrial design profession in industry [Svengren 1995, Persson 2002]. To efficiently utilize industrial design competence, it is often integrated as a part of multidisciplinary teams. The integration aims to unite the industrial design and engineering design functions and to incorporate them into a more homogeneous unit. However, experience shows that members of such teams have difficulties in working together smoothly, since each member has separate functional responsibilities and his or her own view and experience of design work [Svengren 1995].

Industrial designers and engineering designers do not consider the same aspects in the industrial product development work. Industrial designers focus on social utility values, such as aesthetic appreciation, emotions and understanding, while engineering designers usually concentrate on material utility values [Muller 2001]. However, a common denominator is the product to be. Consequently, product representations constitute a common reference in collaborative development [Shrage 1995]. Not only are product representations useful for elaboration, synthesis and evaluation, they also play an important role as a means of communication [Andreasen 1994, Ulrich and Eppinger 2000, Schrage 1995]. This paper is an empirical study on how the use of computer aided design and virtual reality techniques for product representation influences cross-disciplinary interplay in tolerance management work, specifically in the process of estimating the effect of geometric variation on visual quality appearance (VQA).

The overall purpose of the study is to evaluate a proposed tool and method to assess the effects of geometric variation on early concept styling models. A specific effect investigated in this paper is how the proposed tool influences different types of interplay between industrial designers and engineering designers in the geometric evaluation processes.

## **2. Case study**

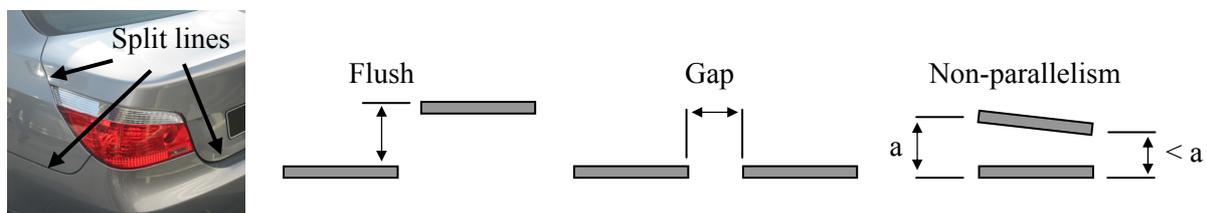
A case study conducted at a Swedish car manufacturing company is based on a new car project including the industrial design and engineering design disciplines. To capture the most recent experience in the design process and at the same time allow project members to obtain feedback on decisions made earlier, a project close to production was chosen. The study was made at the time of

the preparation phase for start of production, and hence it had passed through critical phases related to the issues of interest.

## 2.1 Geometric variation

All manufactured products are affected by geometric variation that contributes to uncertainty in the fulfilment of functional, assembly and quality appearance requirements. Geometric variation causes product dimensions to deviate from the nominal value for all manufactured units. During product design, all digital models are ideal in the sense of variation. The variation is controlled by tolerances that define how much a specific dimension can deviate from its nominal value and by master locating points that lock each part spatially.

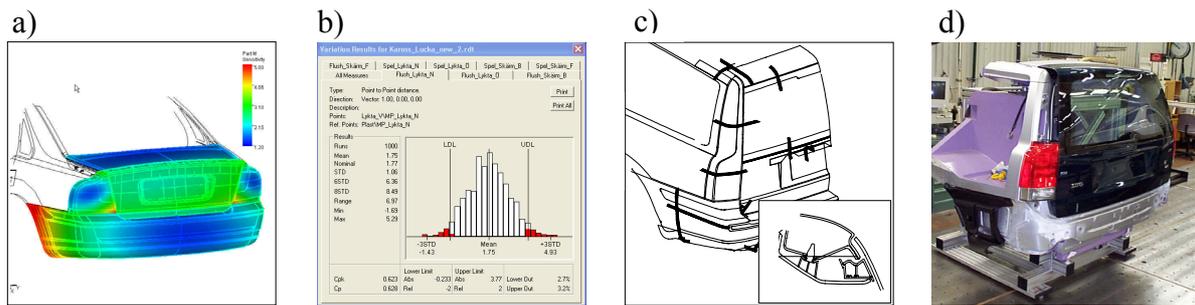
The way parts fit together is affected by geometric variation, for example gap, flush and non-parallelism of split lines, see Figure 1. If a relation deviates largely from its nominal value, this affects the visual quality appearance (VQA), defined as: the "...impression of quality by, just observing the product." [Wickman and Söderberg 2003].



**Figure 1. Flush, gap, and non-parallelism are types of relations that effect VQA of a split line**

## 2.2 Current procedures for evaluating geometric variation

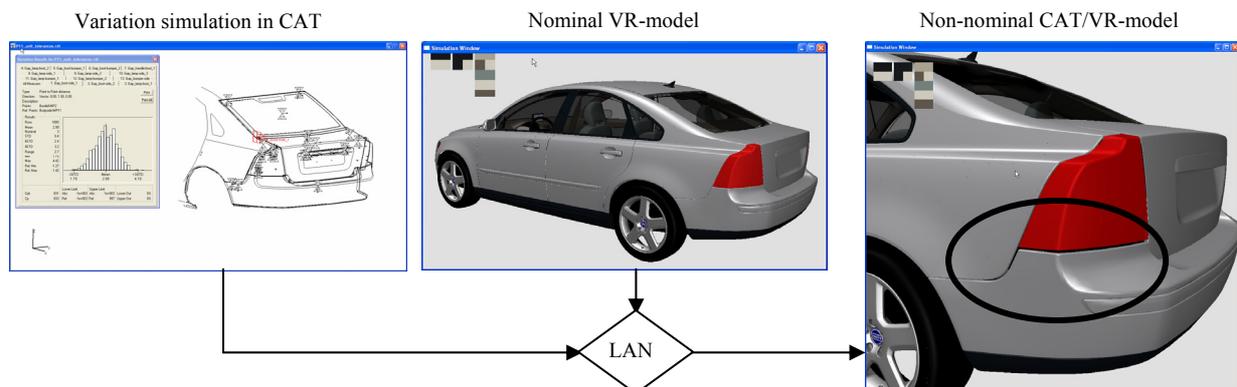
The industrial design and engineering design disciplines are organised separately and located in different buildings. Nevertheless, the evaluation of geometric variation is mainly a joint venture between engineering design and industrial design. Frequent interplay is necessary, since the nature of the problem concerns material behaviour, manufacturability and visually perceived aspects of the product. Industrial design includes the development of visual product form. In the case study, tolerance management constitutes the setting and prioritising of requirements made in compliance with the product form. During the process, several design concepts are proposed. The concepts are iteratively redesigned and successively progress to one final concept. On the other hand, engineering design is technical product development and management of car projects. At specified "toll gates" (check points), digital styling models are released to engineering design for consideration of such aspects as aero dynamics, crash safety, manufacturability, and geometric variation. Based on styling models, the geometric evaluation is initiated. Master location points are determined for the main systems. At this stage, the robustness of concepts is simulated and evaluated, i.e. the magnitude of input variation is determined; see Figure 2(a). Using this analytic procedure, the placement of the master location points can be optimised to minimise the effect of geometric variation without using specified tolerances. When subcontractors and production methods have been identified, tolerances are defined and variation simulations are made, based on the Monte Carlo method, to predict the final outcome of variation; see distribution of simulation results in Figure 2(b). Simultaneously, the dimensional requirements of split lines are defined to obtain the required VQA; during this process, requirements are continuously redefined. Dimensional limitations are given as function sections, according to Figure 2(c). Physical, adjustable mock-ups are made at some stages of the process for evaluating critical and sensitive areas, see Figure 2(d). In the final stage of the development process, physical test series are used to assess VQA for geometric variation. During the process, product information is represented in a variety of ways as shown in Figure 2.



**Figure 2. Four methods to give information about geometric variation; the first three are relatively close together in time, while the fourth is much later: (a) Colour coding of geometrical robustness, (b) results from variation simulation, (c) a function section, (d) and a physical adjustable mock-up**

### 2.3 Proposed tool and method for early evaluation of VQA

To gain feedback on effects of geometric variation early in the design process, a CAT/VR (Computer Aided Tolerancing/Virtual Reality) tool and method was developed. The tool enables evaluation of VQA in a virtual environment; the purpose is to enhance cooperation between industrial design and engineering design. Statistically, the tool calculates the worst case of variation for one or several split lines, for a given number of virtually manufactured units. The result of the simulation is given in a virtual environment where the parts are spatially adjusted according to the simulated variation, see Figure 3. There is a detailed description of the computer tool and method in Wickman et al. [2003].



**Figure 3. Schematic layout of the CAT/VR tool**

Of interest in this study is the contrast between the ways results are represented in the early stages with the current tools, used for evaluation of VQA, and the way suggested for the new tool. The current representations show the results symbolically using colour coded spatial distribution of geometrical robustness and quantitative values of variation, i.e. colours and figures are symbols of the appearance of distribution and amount of variation, respectively. However, for a group of people to evaluate VQA, without the risk of differing mental images, an iconic representation is needed. The proposed tool represents the results iconically. As such, the representation imitates the essential of the modelled item, i.e., the appearance of geometric variation is in correct dimensional relationship in the three-dimensional space [Lundequist 1995, Starkey 1992].

### 3. Approach

The data collection was conducted in two steps. First, the CAT/VR tool was tested and demonstrated in an ongoing car project. During the demonstration, participants assessed and rated the VQA of specified split lines at the rear of the car. Participants could ask questions anytime and speak freely to

each other and the observing researchers. During the demonstration, the researchers collected data by taking notes. The demonstration took place in a show room for virtual environments on two separate occasions. A power wall (large scale back projection) was used for displays; the virtual and simulation environments were displayed simultaneously side by side. Before the study, the test and demonstration described were tried out with research colleagues experienced with similar applications. In the second step, the participants in the demonstration were individually interviewed.

As in Kvale [1996], relevant information from the transcribed interviews was abstracted into a concentrated form and categorised as responses of either the industrial designers or engineering designers. The purpose was to have an overview of general and contrasting answers; it was also to analyse the differences in answers between disciplines. The results are presented in Section 4. In the next step of the analysis, a working model was employed to identify implications of industrial design and engineering design interplay [Persson and Warell 2003].

### **3.1 Data collection sources**

The data was primarily collected from employees at the industrial design and the engineering design disciplines. All of the participants' tasks were closely related to evaluation of VQA from either of the two viewpoints. In the industrial design discipline, five people participated, including senior industrial designers, surface modellers and product visualisation experts. There were eight engineering designers whose positions involved geometry development, including variation simulation and production preparation. Furthermore, data was collected from company specific documentation of the product development process and from simulation and visualisation models used.

### **3.2 Interview method**

The interviews were conducted using a semi-structured interview guide. The purpose of the semi-structured form was to investigate each person's view of conditions within the subject area [Westlander 2000], i.e. their understanding and perceptions of tolerance management and cooperative design work between the industrial design and engineering design specialisations. The respondents were free to specify what to discuss within given topics [Westlander]. The interviews lasted approximately one hour and comprised 45 questions divided into eight topics:

- The project member's core activity, role, and function;
- Current methods and tools for evaluation of VQA;
- Attitudes about incorporating geometric variation into styling models;
- Opinions on the proposed tool and method;
- Required information for the tool and method;
- Work in and conceptions of design quality;
- Implications of the interplay between industrial design and engineering design; and
- General opinions on the subject, and closure.

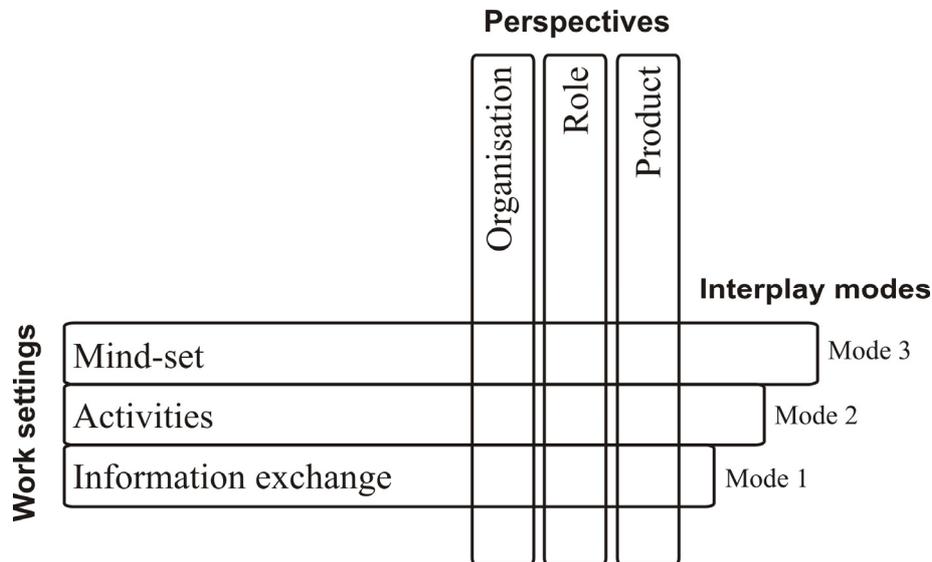
Each topic was introduced with open-ended questions. Following the initial response, further questions were more specific. The approach was intended to capture each person's spontaneous and unbiased viewpoints. The interviews were sound-recorded and transcribed before the data analysis was initiated.

### **3.3 Data analysis**

The data was analysed based on three interplay modes that exist between participants in product development work [Persson, Warell 2003]. The three modes of interplay are: mode 1, how information is externalised and exchanged; mode 2, divergent approaches, methods and tasks; and mode 3, how tolerance management and relations between the disciplines are perceived [Figure 4]. Mode 1 can be studied in the work setting as information exchange, i.e. channels and codes, both visual and verbal (media used for information exchange and interpretations of information). Mode 2 is analysed through activities, i.e. the approach, methods and tasks undertaken in geometric evaluation and the way they are linked between disciplines. Mode 3 is studied through understanding of the mind-set, i.e. the project members' reactions and attitude to the product development work (how the goals, motives,

agendas, work effort, decision making, constraints and exchange of information are interpreted). There is a discussion about the interplay modes in Section 5.

Furthermore, three perspectives were applied to each interplay mode: organisation, role and product perspectives. The organisation perspective includes the management, organisation itself and the process of the product development work. The role perspective is the situation as it is seen from an engineering design or industrial design viewpoint, e.g. differences in knowledge, approaches, methods and tools. The product perspective covers conceptions of the product as well as visual and verbal descriptions.



**Figure 4. Model of analysis approach. Data on work settings was collected and analysed from organisation, role, and product perspectives. Results are discussed according to the interplay modes**

## 4. Findings

The project members' views on the interplay between engineering and industrial designers in general and, on the tolerance management process in particular, are the primary material. Also, the respondents' thoughts about how the CAT/VR tool would influence interdisciplinary activity in tolerance management in the future are discussed.

### 4.1 General views on the interdisciplinary relations of engineering and industrial design

At the beginning of interviews with industrial and engineering designers, several of them brought up problems related to the interdisciplinary work. This arose in open discussions of general problems in tolerance management, without specific questions on interdisciplinary relations. However, the overall opinion about how the disciplines managed to cooperate in product development work was that it is generally satisfactory and better today than some years ago. The relationship was described as open; it was easy to establish contact and to discuss problems. Respondents described the cooperation as a "healthy fighting" or as a "love-hate" relation. Others felt that the level of cooperation depended on one's own personality. Some criticism of the other discipline's way of working was expressed. During the interviews, respondents spoke generally about the relation in terms of "we" and "they", i.e. as a predetermined polarisation between the engineering and industrial design disciplines. Two interviewees felt that even before any problems had occurred, the attitude among the project members was that it is difficult to cooperate.

### 4.2 The role of specialisations and tasks on the interplay

How well project members understand each other's values and tasks was believed by the respondents to be limited. Although industrial designers make an effort to explain important visual product form

issues, engineering designers lack an understanding of the industrial design arguments about how geometric variation affects the final form of the product. Interviewees in engineering design felt that decisions were based on subjective opinions. Conversely, an industrial designer said that some expert terms used in engineering design were difficult to comprehend.

Moreover, respondents felt that product form solutions sometimes lack reality. Project members from each discipline requested more competence in their respective specialisation from the other discipline. Unplanned problem solving processes were perceived as iterative and time consuming. Engineering designers thought that problems could be solved earlier and more easily by transferring tolerance management information to the industrial design discipline. Issues such as weak links between the requirements for VQA and feasibility were brought up as lack of competence. Several respondents from engineering design thought that VQA requirements are sometimes overestimated and do not take into account manufacturability and cost. However, the industrial designers believed that they already have sufficient competence in these matters.

#### **4.3 Issues related to project management**

The project members interviewed believed that some interdisciplinary problems were connected with project management. Within the fluid nature of product development work, project management often makes changes late in the project, when there are fewer options left to make reasonable changes from an industrial design point of view. An issue contributing to barriers between the disciplines is that management seems to give tolerance management lower priority than other parts of the product development process.

Respondents from industrial design described some problems arising from contradictory directions from management. Industrial designers felt that engineering designers prefer traditional solutions to new and creative ones and that they lack “pioneering spirit” and inspiration. Engineering design was described by respondents as being more administrative than innovative, as it once had been. The management expected industrial designers to create something new and unique; engineering designers, who have to consider requirements and cost, must often rely on subcontractors, who were described as not being interested in creative novel solutions.

#### **4.4 Issues related to the conceptions of tolerance management**

Respondents from both disciplines have the same view on what is included in the VQA concept. Furthermore, they also regard geometric variation as a factor influencing VQA. However, there is no common definition of how the product form is affected by geometric variation, which indicates that this issue is not taken into account in the formal tolerance management process.

Interviewees’ individual description of the tolerance management process and evaluation of VQA differed according to their disciplines. Project members did not mention the other discipline’s tasks and processes. They also lacked a common process and a common way of evaluating the work. Furthermore, the process varies for each project. Several iterations sometimes had to be made before a solution could be agreed upon. Information transfer was, by some respondents, perceived as problematic since information needed from the other discipline about, e.g. rating of split lines, VQA requirements and system solutions for master location points was sometimes incomplete or missing.

The study also revealed inconsistencies in the effort expended by the engineering versus industrial design processes. Respondents from industrial design perceived an unbalanced collaboration regarding the amount of work input from each discipline in the early stages. Industrial design contributes several design solutions, whereas engineering design generates only one technical solution. Furthermore, when industrial design works with several styling solutions in a process, only one of them is analysed for geometric variation. The respondents suggested that multiple technical solutions should also be developed and evaluated to determine effects on VQA.

Separate locations and limited physical access to the industrial design discipline was perceived by engineering designers as a barrier to informal meetings and continuing cooperative work. However, the work is considered more efficient today than before. Project members make more efforts to cooperate, and access restrictions to the industrial designers have decreased. Furthermore, the members stated that the joint meetings maintain valuable contacts and support discussion. However,

many people suggested that meetings should be more frequent in the early stages and should include the development of solutions by joint teams that include industrial designers, engineering designers and subcontractors.

#### **4.5 Opinions on early consideration of geometric variation and VQA**

To evaluate geometric variation at an earlier stage, industrial design has to deliver priorities of requirements and engineering design has to deliver system solutions of master location points. Industrial design project members expressed reservations about consideration of geometric variation in early stages, as the geometries for this go through many changes. Although some geometric variation is considered by industrial designers as early as the sketching stage, e.g. by avoiding sharp corners and junctions where several split lines meet, the engineering designers strongly believe that geometric variation must be dealt with more extensively in the early stages and that industrial designers should have more confidence in the estimations made by engineering designers. Interviewees from industrial design also believed that the determination of master location points should be completed earlier in agreement between engineering and industrial design, however, they should not think this should be allowed to influence the intended product form. Industrial design respondents stated that the product form could be “diluted” if the consideration of geometric variation is started too early in the project. Industrial designers believed that master location points should be placed to suppress the effect of variation in the product form, but that the product form should not be adjusted according to the master location points.

#### **4.6 Opinions on the handling of problems related to VQA**

There was a joint opinion that it should be the engineering designers who solve anticipated problems related to VQA. Too much compromising between technical and aesthetic aspects could spoil the original intent of the product form. The interviews revealed that engineering design does show consideration for industrial design’s intentions and wants to avoid interfering with the product form. According to the respondents from engineering design, the product form should not be changed unless industrial design approves it. All respondents regard failure to stick to agreements as a problem. Often, decisions are changed and agreements ignored, which results in more iterations. It was stated that established hard points (agreed positions of geometries) had been overlooked during product form development. Most respondents believed that solutions agreed upon should in general not be changed during the project.

#### **4.7 Interdisciplinary effects of integrating the CAT/VR tool**

Members of both disciplines believed that the new CAT/VR tool would contribute to increased understanding between them. It was also believed that the tool would help to increase the common awareness of goals, and that it would foster discussion. Engineering designers considered it useful to learn to see things from the customer perspective. The tool would also make it possible to see how a single detail affects the overall product form, which would eliminate speculations about the results. It was thought important to focus not only on the result but also on the underlying cause of a problem and how to solve it. According to the interviewees, although the tool itself would not contribute to better understanding, a common effort to use it would.

The general opinion among the respondents was that there is a lack of suitable product representations for evaluation of tolerances. Several types of product representations are currently used for analysing feasibility and VQA. Engineering designers use results from variation simulation (Figure 2b) and function sections (Figure 2c). Although engineering designers appreciate the difficulty in evaluating VQA based on such data, they still expect industrial designers to should use them for estimating VQA. Physical adjustable mock-ups (Figure 2d) are used in the process, but infrequently, and then only for evaluating critical areas of the car. The mock-ups are also considered too “rough”, in the early stages, for such evaluations. Respondents believed that the CAT/VR tool would help to show how engineering design aspects influence the visual product form and vice versa. Engineering designers

would be able to consider manufacturing aspects and industrial designers to consider VQA concurrently.

#### **4.8 Proposals for application of the CAT/VR tool**

Project members believed that the CAT/VR tool could be used for collaboration during meetings on different levels, such as working meetings and strategic meetings. People with differing competence could use it as a tool to convey their aspects in decision making. An expressed advantage of the tool was that using visual depictions of variation effects of the product is superior to using of solely the spoken word and texts when conveying information for decision making.

To gain beneficial effects of enhanced collaboration, it was stated that the tool has to be easy to use and easily integrated in daily work. The study showed that several interviewees considered that the usage of a power wall is beneficial, as it allows several project members to evaluate geometric variation and VQA concurrently. However, it was believed that the users had to be experienced in interpreting reality from virtual reality models. It was suggested that both the engineering and industrial designers bring multiple solutions so that different combinations could be tried out, instead of using only one technical solution and several visual form solutions.

All respondents agreed that the CAT/VR tool would provide a suitable product representation for supporting and stimulating interdisciplinary collaboration. However, respondents perceived the engineering design discipline to have an advantage in being able to support their arguments with technical facts and costs. There was a concern that it could be more difficult to make some decisions when using the CAT/VR tool, since people without industrial design competence could interfere with the development of the product form. Industrial designers were concerned that the tool would be used as an additional means for making decisions in favour for engineering design. Engineering designers could also see that the tool would make it easier to persuade industrial designers and help them understand the visual effects of variation. Conversely, another belief was that the tool could be used to support industrial designer's arguments by pointing out visually sensitive areas of the product form.

### **5. Discussion and conclusions**

The seven major problems that affected interdisciplinary design work in this study are concluded to be:

- Preconceptions that the interplay is a problem;
- Lack of understanding of each others' tasks, goals and motives (subjective versus objective explanations and specialised terminology);
- Lack of trust (agreements are ignored and requirements overestimated);
- VQA evaluations given low priority by management (not a formal part of the process, varies from project to project);
- Uncoordinated processes (creative process versus consideration of geometric variation, information not received when needed, unbalanced work input, problems occur too late for satisfactory solution);
- No common tool or forum for representing VQA; and
- Different opinions about the way the proposed tool would change the interplay.

Analysis of the issues brought out by the interviews revealed some consequences of tolerance management. Next, the issues are analysed according to three modes of interplay: mode 1 (how information is externalised and exchanged); mode 2 (divergent approaches, methods and tasks); and mode 3 (how tolerance management and relations between the disciplines are perceived). All three modes are analysed from the organisation, role and product perspectives. Also, the role of the CAT/VR tool and method in the interplay is discussed.

#### **5.1 Mode 1: creating prerequisites for communication**

A prerequisite for achieving interdisciplinary cooperation is established communication channels. Since the disciplines are separately located, continuous channels such as informal meetings are limited and, thereby, so is continuous cooperative work. When cross-disciplinary communication relies mainly on formal meetings, telephone conferencing and e-mailing, as in the case studied, access to fellow project members is reduced and the understanding of communication becomes more critical.

By using the CAT/VR tool for visual communication of goals and consequences of changes, a holistic concept of the VQA is possible. With this type of product representation, immediate feedback on changes of master location points, split lines and the visual product form, can be established. It would be possible to identify consequences from both the engineering and industrial design perspectives, since changes of solutions can be altered on the basis of a common idea in a common forum.

A problem revealed by the study is that the types of product representation used had a weak connection to the qualitative evaluation of VQA. When using quantitative data for evaluating VQA, the result had to be subjectively imagined. The proposed tool, on the other hand, corresponds to the qualitative, visual evaluation. Furthermore, as an iconic product representation, it communicates results close to reality. A product representation that represents properties of VQA, such as surface continuity, can be interpreted by all stakeholders in the same way. The visual language as a communication code is also regarded by the project members as powerful in decision making and as such serves as a universal language.

### **5.2 Mode 2: interrelating disciplinary activities through interaction**

The disciplines are physically separated, which limits continuous contact and insight into each other's activities. For a project group that includes both disciplines a statement of the members' approach, methods and tasks, and their coordination, is needed to gain an understanding of the other discipline's activities. The study showed that although the engineering and industrial design processes had a strong interdependency, they were not considered a common process, except for the fact that information was transferred between the disciplines. Reasons for this included that project members did not receive the same instructions from management, that the process of tolerance management proceeded in an "ad hoc" manner and the disciplines had developed differing tools and methods. The absence of an articulated term for this type of problem indicates that it has not formally been considered in the work process. A descriptive approach, dealing with the disciplines' respective activities and how they are interrelated would provide a contextual comprehension of the other discipline's tasks, and how they relate to the internal work of one's own group. Furthermore, respondents in the study believed that the suggested tool and method would enable a common approach as well as a common reference in tolerance management.

### **5.3 Mode 3: achieving interdisciplinary understanding through collaboration**

Aesthetic aspects of product appearance are mainly based on subjective factors such as perception, attitude, socio-cultural values, and experience. It is therefore difficult to describe explicitly underlying motives for the appreciation of a specific product form. Engineering designers use scientific methods for testing and solving technical problems. The motives of industrial design that influence engineering design work are implicit and, consequently, difficult to evaluate objectively. In the case studied, the engineering design processes seldom take into account intuitive and tacit knowledge.

Overall, the study revealed a positive attitude towards interdisciplinary collaboration. However, subjective industrial design aspects had to be specifically taken into account; otherwise they would, to a certain extent, be overruled by aspects other than the appreciation of visual product form. To achieve collaborative design, a mutual understanding of the differences between disciplines and a willingness to collaborate are needed. It was also believed by the respondents that each discipline sees its own sphere of responsibility as the most important. The presupposed opinion that interdisciplinary problems will arise generates a competitive atmosphere, not only of a desirable nature, which is a source of conflicts. To achieve the collaborative effects of the tool, users should feel an equal input in relation to the outcome, i.e., the CAT/VR should not be used to offer arguments or objections, but to promote joint solutions to a joint problem.

### **5.4 Concluding remarks**

The study aimed to better understand the interplay in tolerance management work from a practical, day-to-day perspective. Some of the problems were connected with the management, whose opinions are not included in this study. Furthermore, tolerance management was examined at only one company, which allowed for an in-depth study; however, generalisations cannot be made. It should

also be noted that the proposed tool investigated had not previously been used in a formal project, although several respondents were familiar with CAT/VR and had tried it before.

The problems discussed in the interviews were openly referred to in daily work. This study also revealed a willingness among the respondents to understand the process from the perspectives of both disciplines. The openness at the company allows discussion of anticipated problems.

The model of interplay modes is subject to further development and theoretical anchoring.

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