Quantification of Applicability of Shape Modelers in Collaborative Conceptual Design

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ABSTRACT

Demand from the industry motivated software vendors to address the issue of supporting collaborative conceptual design by software tools. Considering the fact that a vast number of software tools have been developed to support a mixture of design activities of collaborative conceptual design (i.e. idea generation, presentation, reasoning, and modeling) from various aspects (e.g. functionality, shape, structure, behavior, sustainability, and service), selecting the most appropriate tools is a challenging task. One of the key problems is that there are no objective techniques and procedures to compare the tools and make a decision. We propose a new quantitative approach, which evaluates shape modelers by taking into consideration the cognitive aspects of collaborative conceptual design. Conceptual design is of a dynamic nature that originates in fast idea generation and modeling, evolving concepts, and coexistence of alternative solutions. On the other hand, collaborative aspect should be supported by expressive models that allow the collaborating partners to easily exchange ideas. Based on these attributes we established three criteria for evaluating shape conceptualization systems i.e. speed of externalization, variability of the model, and expressiveness. The speed of externalization is simply quantified as the time that the designer spends on thinking about the way of modeling a given shape with a certain CAD system. Variability of a model, which is a capacity to explicitly represent variations of a product concept, and expressiveness, which is the understandability of the model, is quantified by measuring dissimilarities of shapes generated by a given system. This paper presents the theoretical background of this testing method, as well as its application for shape conceptualization systems

Keywords: Collaborative conceptual design, speed of externalization, variability of shape, expressiveness of shape, shape similarity.

1 INTRODUCTION

Tools for computer support of collaborative conceptual design have flooded the market of CAD software. To compare and evaluate these tools, various testing methods are needed to be developed, which are able to support e.g. benchmarking in terms of the characteristics of the modeling process and the properties of the developed models. The process of collaborative conceptual design involves a set of activities e.g. idea generation, presentation, reasoning, and modeling, in which several aspects (e.g. functionality, shape, structure, behavior, sustainability, and service) are considered and brought into synergy. Representation of a product model in most of the cases depends on the particular aspect(s) considered in a given phase of design. Being strongly dependent on the other aspects of design, shape modeling plays a significant role in collaborative shapes conceptualization. That is the reason why the authors focus on the evaluation of shape modelers dedicated to collaborative conceptual design.

To compare various shape models of different CAD systems several approaches have been developed. They can be classified based on the shape representation [10]: (i) 2D contours, (ii) 3D surfaces, (iii) 3D volumes, (iv) structural models, and (v) hybrid. In our approach we use mesh representation of 3D volumetric shapes, which provides compatibility to most of the shape modelers and supports various investigations on the basis of geometric and appearance attributes. A possible principle of comparing shapes by considering low level geometric information is statistics. Ankerst et al. created statistical shape distribution functions of shapes by decomposing the boundary into sectors around the centroid of the model and generating shape histograms [1]. To measure the similarity of shapes, their shape distribution function is compared. Osada's extended this approach to non-manifold models [14]. He created shape functions based on measuring the distance between two random points. Comparing shapes based on their histograms is efficient if the dissimilarity of shapes is high. However, in the case of two very similar shapes, small dissimilarities can hardly be detected. Another simple approach is evaluation of distances between feature vectors in a multidimensional space. Feature vectors can be composed of global geometric entities, such as algebraic moments [4], ratio of volume and surface area [6], eigenvalues of adjacency matrix of a skeletal graph [9]. The main advantage of this methods, that relatively large number of shapes can be compared within a short time in a database, which stores the values of feature vectors. However, these feature vectors can fail to capture the specific details of a shape and their robustness depends on a given combination of geometric entities.

To compare shape modelers from the point of view of supporting collaborative modeling activities, the authors started out from the cognitive model of collaborative shape conceptualization. Three criteria have been identified as primary metrics for shape modelers: speed of externalization, expressiveness, and variability. Speed of externalization is measured in terms of the time spent on thinking about the way of modeling a given shape or shape element with a certain shape modeler. Expressiveness and variability are measured by comparing the shape models created by different CAD systems. Expressiveness is quantified as the achievable similarity between the targeted shape and the designed model. Variability is measured as the dissimilarity between the two extreme shapes explicitly or implicitly represented by one generic shape. For measuring dissimilarity/similarity of shapes, the authors proposed a method that combines the most advantageous elements of the feature vectors and shape histograms approaches. The feature vectors are defined based on the histograms of various morphological attributes (structural deviation, location difference, and curvature difference) and some global geometric attributes (e.g. topological genus) of shapes. They are projected to a reference sphere that has the same volume as the investigated model. This paper presents the theroretical background of establishing the evaluation criteria for shape modelers, the development of a metrics to quantify the evaluations criteria, and an application in which two shape modelers are compared and tested from the point of view of their applicability in collaborative conceptual design.

2 FUNDAMENTALS OF DERIVING CRITERIA

For the simple reason that the support of collaborative conceptual design has already been addressed by development of dedicated software tools on the basis of cognitive models, the authors places the starting point of deriving evaluation criteria for shape modelers on the same principles. First, a cognitive model for conceptual design is presented with the aim to identify the characteristics of this design activity. Then, this model is placed into a collaborative context and investigated to determine the requirements to address the aspects of collaboration.

2.1. Cognitive model of conceptual design

Conceptual design is preliminary to the detail design process of artifacts, with the aim to generate product concepts for further processing. Conceptual design is dominated by iterative idea generation, presentation, reasoning, and modeling, which in large part still remain tasks for human beings. These activities and their relations are shown in Fig. 1.

The idea of a product appears in a general form, and the conceptual elements are individually looked for and brought into synergy. Therefore, the focus of designers alternates between the parts and the whole of the product [20]. Idea generation relies on a series of mental breakthroughs to generate solution principles [11]. Nevertheless, it has also been shown that in general the initial idea is rough, incomplete and abstract, details are missing and the design concept is more a cloud than a definite outline [5]. These cloudy concepts crystallize in the course of time and are transformed into a clear and complete image of a solution to the problem [19]. This latter characteristic is identified as the evolutionary nature of idea generation.

Once an idea is formulated in one's mind, it has to be presented for various purposes. Presentation enables the designer and in particular the co-designers to understand the design problem, develop design solutions to the problem, and then evaluate the potential solutions that have emerged and have been developed. Versitjnen found that idea generation does not necessarily require presentation for the synthesis itself,

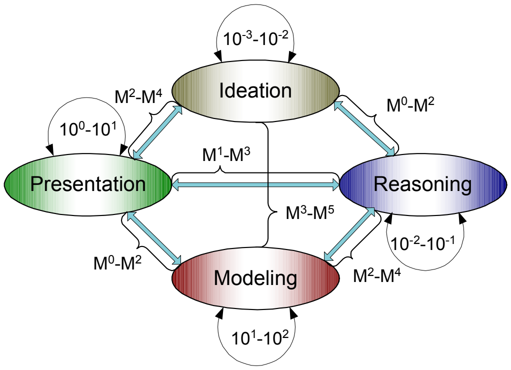


Fig. 1. Cognitive scheme of conceptual design (M=magnitude, unit: [sec]) [8]

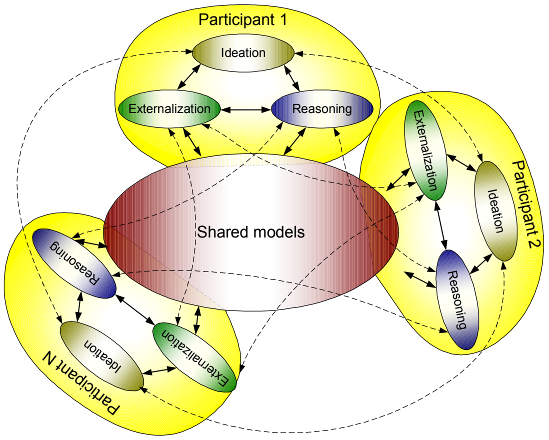


Fig. 2. Cognitive scheme of collaborative shape conceptualization

but it benefits from the accompanying externalization through analysis and reasoning [21]. In addition, presentation plays an influential role in communicating ideas to other human beings and by facilitating sharing of ideas in a collaborative development of alternative solutions for design problems. Presentation triggers a thinking and reasoning process, in which the reflections of the design concepts appear. The designers think about the correctness of the ideas and representations, and reason about the formation of the solutions. In spite of the abstract description of design concepts, shared understanding has to be achieved among the design participants. In order to fill in communication gaps between designers, customers, and design concepts, each participant in the collaborative process has to be aware of the meaning of the symbols of presentation used. A shared understanding of the design concepts enables the designers to reason on the same level of comprehension about design concepts. Thus, the ultimate goal of reasoning is to trigger, mediate, control, evaluate, and test the design concept against the requirements and to explore alternative, better solutions [15].

The three activities of conceptualization, namely idea generation, presentation, and reasoning, form an intuitive creative loop and set the stage for more formal modeling. Modeling converts the tentative representations of the design concepts into various structured descriptions, called concept models. The product concepts quickly evolve and several alternative solutions coexist. The data and knowledge captured by conceptual modeling are in general abstract, incomplete, and imprecise. The computer tools developed for computer modeling and processing must be able to cope with these properties of conceptual design and to handle the wide varieties of related information. A unique criterion for shape conceptualization is the speed of externalization, which should be maximized.

2.2. Cognitive model of collaborative shape conceptualization

Collaborative design denotes design activities in which more than one person is involved and works on a common design problem, having a common goal or intent. Collaboration is possible when the collaborators share activities and information to achieve the common goal. The shared understanding should be facilitated by an explicit representation, which should comprise both visual and semantic model [18]. Effective collaboration is achieved when the collaborators share design tasks, communication, representation and documentation [12].

In a comparative study of remote and proximal design teams Garner found that working remotely resulted in a ‘highly significant’ 42% decrease in generating of design concepts but no significant difference has been found in the results [7]. It has been explored that the remote teams preferred to work-up existing sketches rather than create new ones. Further analyzing these experiments we could conclude that, on the one hand, there is a need to consider the emergence of multiple variations of the design, on the other hand, rationalism of information processing and communication calls for some fort of unified representation. This implies that virtual collaboration requires a modeling technique, which is able to capture several concepts in one model providing simultaneous access to all participants. As an attempt to support collaborative design Chan developed a system, in which collaborating designers can edit models in real time. The different versions of the same model are represented in a single CSG tree [2].

Recent studies showed that from the cognitive perspective, designers deal with the same type of problems no matter they are working alone or in teams, albeit with different degrees and spans of commitment [3]. The above mentioned facts stimulate us a basis to propose a model for collaborative shape conceptualization, which is shown in Fig. 2. The organization of this figure resembles the system architecture, called distributed and integrated design environment, presented by Prasad et al. [16]. In distributed-integrated design environment, distributed designers usually have their own domain systems along with a central service module called a sharable workspace.

3 ESTABLISHING EVALUATION CRITERIA

Based on the cognitive scheme of conceptual design, we identified speed of externalization as the most important criterion in the use of a shape conceptualization system. Externalization is the conversion of mental images to formal schemes such as formulas, patterns, diagrams, forms, structures and shapes, and offers the possibility to use formalized schemes in design. Hence, the speed of externalization depends on design tools and representation of models used in conceptual design. Note that the speed of processing information is also an influential factor for the speed of the design process as a whole. It is primarily determined by the speed of the computer powering the CAD system. However, this aspect is more related to benchmarking of the computer system than to the actual domain testing of a conceptual design system. Consequently, the effective support of fast conversion of the ideas will be used as the first criterion for domain testing.

The second criterion originates in the collaborative aspect of conceptual design, which implies that designers should understand each other's intent and be able to share the model in a product conceptualization process. It can be best achieved by using representations of the model that lend themselves to an explicit (non abstract) and expressive representation of the shape. Expressive models can speed up the design process by reducing the time spent on: (a) understanding the model, (b) unnecessary questions of participants, and (c) explanations by the creator of the model. Note that the speed of externalization and the speed of the design process are not the same.

The third criterion is the variability of the model used to represent design concepts. The need for variations in design concepts is natural in conceptual design and in collaboration. In conceptual design, variability of the model represents a range of shapes from the possible design solutions, which can be captured in a single model. In collaboration, variations of the model allow for various users to follow different paths of product conceptualization and to develop different solutions to a given problem. Using a fix model to represent several design concepts is difficult and limits the exploration of possible solutions, which are available in the modeling space. Consequently, the aim is to use a model that is able to grasp the largest subset of possible solutions from the design solution space.

Fig. 3 shows the relations and the dependencies of the three evaluation criteria. The criteria are not independent. The speed of externalization is inversely proportional to the expressiveness of the model and, to some extent also to the variability. To create a model that expresses all aspects and details of the shape, local geometric elements need to be defined, which in turn requires more effort and time from the designer. We found that the variability and expressiveness of the model are inversely proportional, since under-defined shapes leave more freedom for variations than their well-defined counterparts. The correspondence between variability and the speed of externalization is a proportional dependence, meaning that spending less time on creation of the model leaves more freedom for thinking as well as for further elaboration. Our aim is to find the right balance in terms of fulfilling these three criteria.

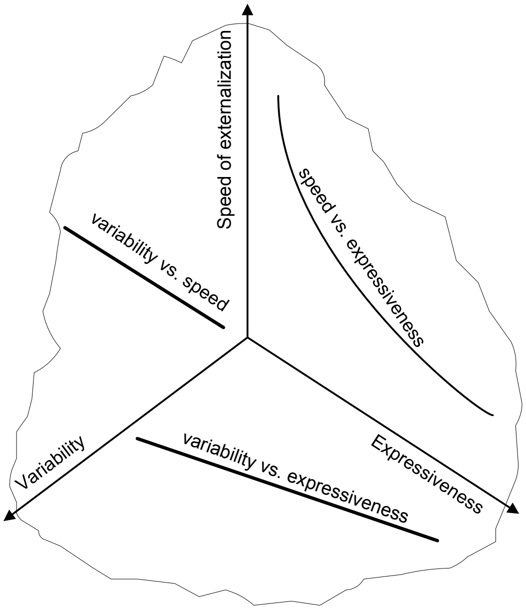


Fig. 3. Dependencies of evaluation criteria

4 DEVELOPING METRICS FOR THE EVALUATION CRITERIA

To make a quantitative evaluation of shape modelers against the formerly introduced criteria possible, two methods have been developed and applied. The first method focuses on the measurement of shape dissimilarity, which can be used to directly measure variability, and to indirectly measure expressiveness. The second method measures the time that is spent on the externalization of a given shape.

For the simple reason that expressiveness of a shape is extremely difficult to measure in an explicit manner, i.e. quantitatively, we introduced an implicit approach to the quantification. This approach relies on the concept of shape dissimilarity. Numerical values of shape dissimilarity were used in experiments. Shape dissimilarity has multiple aspects. To measure the dissimilarity of two shapes, three shapes characteristics are taken into account: (a) topological genus (b) structural complexity, and (c) morphological articulation. The topological genus, *G*, of the shape is dependent on the number of holes in the shape. The topological genus of a shape is zero if it is homeomorphic to a sphere, that is, it does not contain any hole.

The structural complexity of a shape can be quantified based on the (structural) deviations relative to a sphere. Three components of structural complexity have been identified: (a) generic shape structure, D^{SG}, which characterizes the difference of the dimensional ratios of the shape and the sphere, (b) global shape structure, D^{SGL}, which represents the difference of the topology of the shape and the sphere, and (c) local shape structure, D^{SL}, which stands for local structural dissimilarities between the shape and the sphere. Thus, structural deviation, D^S, is defined as a triplet so that $D^S = (D^{SG}, D^{SGL}, D^{SL})$. The generic shape structure is defined by the ratios of the sides of the bounding box of the shape. It represents the geometric deformation of a shape compared to the sphere. The global structure of the shape is calculated based on the topological deviation of a shape relative to a sphere. The sphere is positioned at the geometric centroid of the object. In case of similarity, each point of the sphere has only one corresponding point of the shape, which is in radial direction from the geometric centroid. The global structural deviation of a shape can be calculated as follows: $D^{SGL} = \int_A NdA/A$, where D^{SGL} is the global structural deviation of shape and the sphere, dA is surface element on the sphere, N is the number of surface elements on the shape corresponding to a given surface element of the sphere, dA', and A is the surface area of the shape. Note that the correspondence between dA and dA' is defined by a radial projection from the geometric centroid. The local structural deviation of two shapes is expressed in terms of the space that they occupy. To be able to assimilate them, the two shapes (target, S_T, and subject, S_S) must have the same volume, should be positioned relative to each other by their geometric centroid, and should be orientated by their bounding boxes. The integral of the distance of a set of points on the subject shape's surface from the target shape surface expresses the local structural deviation. Mathematically, it can be determined as follows: $D^{SL} = \int_{A_S} | d_T - d_S | dA_S / V$, where D^{SL} is the local structural deviation of shape S_S from shape S_T, dA_S is the corresponding element surface to dA_T, d_T is the distance of dA_T (elementary surface of the target shape) from the geometric centroid, d_T is the distance of dA_S (elementary surface of the subject shape) from the geometric centroid, and V is the volume of the shapes.

The morphological component of dissimilarity expresses local geometric dissimilarities. To quantify it, the curvature dissimilarity of two shapes should be measured after the shapes have been positioned and oriented as above. The morphological component is calculated for a dA_S element of the shape as follows: $D^M_{dA_S} = (\int_u | \kappa_{Tu} - \kappa_{Su} | du + \int_v | \kappa_{Tv} - \kappa_{Sv} | dv) / dA_S$, where $D^M_{dA_S}$ is the curvature deviation of a dA_S surface element on shape S from the corresponding surface element dA_T on shape T, κ_{Tu} is the curvature of shape T in u direction, κ_{Tv} is the signed curvature of shape T in v direction, κ_{Su} is the signed curvature of the shape S in the u direction, κ_{Sv} is the curvature of the shape S in the v direction. For the whole surface, A, D^M_A is calculated as follows: $D^M_A = \frac{1}{A} \int_v D^M_{dA_S} \, dA$. The sign of the curvature is positive if the shape locally convex, otherwise, it is negative. The feature vector of dissimilarity is combined from these components as follows: $D = (D^G; D^{SG}; D^{SGL}; D^{SL}; D^M)$.

Having a shape evaluation on the basis of pure quantitative elements is in conflict with the principles of shape perception. Research in shape perception found that visual stimuli varying on a monotonic scale are often not perceived as gradually changing. Instead, the elements along this continuum are often perceived as belonging to discrete categories (Newell and Bülthoff, 2002). Shape perception plays a significant role in the course shape modeling, when the designer continuously interacts with the shape and implements modifications based on his/her shape perception. The authors proposed a categorization of shapes based on various dissimilarity measures.

To interpret the results of the assessment of the dissimilarity of shapes five categories have been identified on the latent range of values: (a) dissimilar, (b) comparable, (c) similar, (d) equivalent, and (e) congruent. Fig. 4 shows the structural and morphological deviation of a set of shapes compared to a sphere. These shapes have the same topological genus and have no generic, or global, structural deviation. In this assessment, we found that the domain of dissimilar shapes is in the range of $D^M > 17$ from morphological aspect and $D^{SL} > 1$ from point of view of local structure. Two shapes have been considered comparable if $17 > D^M > 10$ and/or $1 > D^{SL} > 0.7$. Similar shapes are in the range of $10 > D^M > 4$ and/or $0.7 > D^{SL} > 0.3$. Two shapes are practically equivalent if $4 > D^M > 0$ and/or $0.3 > D^{SL} > 0$. Two shapes are congruent if $D^M = 0$ and $D^{SL} = 0$. If the topological genus, generic and/or global structural deviations of two shapes are different, then the shapes are said to be dissimilar. Note that similarity of two shapes can be different from the aspect of local structure and from the point of view of

$D_{1,5}^{M}=20,\quad D_{2,5}^{M}=15.2,\quad D_{3,5}^{M}=9.6,\quad D_{4,5}^{M}=1.7,\quad D_{5,5}^{M}=0,$

$D_{1,5}^{SL}=1.2,\quad D_{2,5}^{SL}=0.9,\quad D_{3,5}^{SL}=0.45,\quad D_{4,5}^{SL}=0.05,\quad D_{5,5}^{SL}=0,$

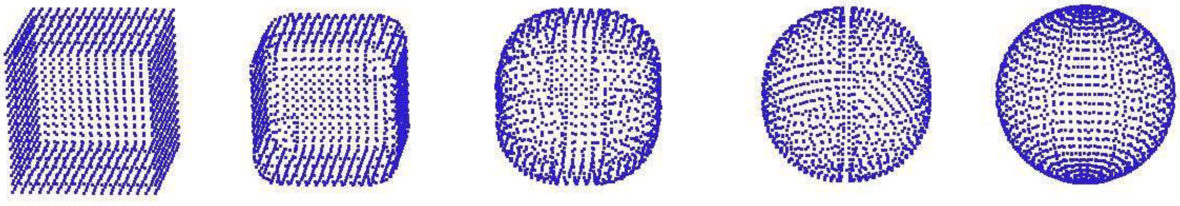

(a) (b) (c) (d) (e)

Fig. 4. Curvature and morphological deviation of shapes

morphology, and the above mentioned categories are based upon a subjective categorization.

To measure the speed of externalization, the elapsed time is divided into three parts. The first part is the time of externalization, t_e, that is the amount of time that the user spent on thinking about the method of externalization. The method of externalization is related to the intuitive or rational selection of a set of system commands to realize a given shape. The second part is the time of processing, t_p, that is spent by the computer to execute the commands of the user. The third part is the time of menu-handling, t_{mh}, that is the amount of time spent by the user to communicate the commands to the shape modeler. The relation between these components is described as follow: $t = t_e + t_p + t_{mh}$, where t is the elapsed time spent on the experiment. The time of externalization is determined by: $t_e = t - t_p - t_{mh}$. To be able to interpret the acceptable domains for the speed of externalization, we refer back to the cognitive model of shape conceptualization. An acceptable range of values is in the domain of [1, 10] seconds.

5 EVALUATION OF SHAPE MODELERS

In this section we apply the above introduced assessment methodology to an “academic” shape modeler, called vague discrete interval modeler (VDIM), and to a commercial system. The goal is to assess the applicability in collaborative conceptual design. VDIM has been developed by the authors with respect to the intrinsic characteristics of collaborative conceptual design. To familiarize the reader with the principles of VDIM, first a short overview is given.

5.1. The concept of VDIM

At the begin of the development we studied the means offered by the commercialized modeling systems as well as the needs of the industrial designers for new modeling approaches supporting shape conceptualization. The results of the first study, which was based partly on the related publications and partly on experimenting with commercialized (or pilot) systems, were summarized in [17]. As far as the opinions of practicing designers are concerned they indicated the need for:

- handling impreciseness in modeling the geometry of the shape,
- coping with incompleteness of structural modeling of the product,
- tolerating abstractness following the evolutionary aspect of the design process,
- producing alternatives of shapes in terms of size and shape variation,
- intuitive model building tools to create and modify the models of the product, and
- application of physical principles for testing and manipulating shapes.

Based on these requirements the concept of Vague Discrete Interval Modeling (VDIM) has been developed. VDIM is a modeling technique dedicated to the support of shape conceptualization. VDIM is vague from that sense that (a) it models a cluster of shapes by one representation allowing for combining a nominal shape with its domain of variance, (b) it represents the structural relationships between shape components, which can build up the shape completely or incompletely, and (c) follows the development of the shape by means of dedicated modeling methods and tools. VDIM is discrete since the representation of the geometry is composed from discrete entities. Finally, VDIM is an interval modeling technique, in view of the fact that it describes the shape by specifying the position of points by an interval.

The fundamental modeling entity of VDIM is the particle, or more precisely, coupled pairs of particles. Particles take care of providing positional and morphological information for the geometric representation. The reference points of the particles are uncertainly specified by a distribution called metric occurrence. To be able to model the physically based behavior of a shape, particles are attributed by mass and velocity. Coupling of particles makes it possible to introduce various physical relationships and constraints in order to provide the means for a behavioral simulation based on the vague discrete interval model.

A vague discrete model is a composition of a set of particles. The minimal and maximal overlaying surfaces generated on the extremes of distribution specify the boundary of the vague discrete model. The images (actually, image points) of the particles on the two boundaries of the distribution interval are connected so-called distribution trajectories. The distance between the neighboring particles is the characteristic discreteness of the vague discrete interval model. The distribution interval represents the morphology of the described cluster or family of shapes, and is used to derive instance shapes of the same morphological character. A vague discrete interval model can represent global shapes, local shapes, and any composition of them. The vaguely defined particles contained in a VDIM support multi-resolution manipulation of shapes. To facilitate the generation of particle systems, volumetric operators have been introduced, which are able to calculate the Boolean union, difference, intersection, and Minkowski sum of vague shapes.

If a varied shape instance is required, the concept of rule-based shape instantiation offers the necessary means for it. The shape formation rules are defined based on the knowledge related to the application and converted to shape instantiation functions. An instance shape is actually a system of discrete particles of zero metric occurrences (or distribution trajectories). This approach indicates the consistency of the representation of vague interval shapes and nominal instance shapes. The instance shape is always inside the interval and resembles either one of the interval boundaries, or both of them, depending on what has been considered to be the base of instantiation. Instantiation specifies the position of the reference point of the particles along the distribution trajectories. The geometric position of the instantiated zero-distribution particles is determined by the shape instantiation function, which are derived from shape formation rules relevant for the application at hand.

There are two fundamental issues here to be solved. First, the qualitative or quantitative shape formation rules have to be converted to shape instantiation functions. Second, the VDIM may represent a complex shape whose regions need to be instantiated individually by different functions and the instantiated regions have to be reunited. To convert qualitative shape formation rules to mathematical functions efficiently, the concept of effect function has been elaborated. To solve the problems of region-oriented instantiation, three techniques have been considered, namely, simple, compound and constrained instantiation. Simple instantiation is applied when the whole particle system can be mapped to an instance by a single effect function. Compound instantiation applies multiple effect functions on the same particle cloud and try to smoothly connect the instantiated regions by fuzzifying them in the transitions strips. Constrained instantiation applies multiple effect functions on multiple particle systems and applies constrained fuzzyfication to merge the instance shapes.

As the major application field of VDIM is conceptual design, it is beneficial to integrate physically based modeling tools to VDIM. These means facilitate the evaluation of the nominal instance shapes by simulating their behavior. The geometric representation of VDIM is directly used in physically based modeling with the extension of the geometric model by internal particles, and the physical relationship between the particles. The material properties of a physical object are set by the coefficients of internal forces i.e. (damping constant, Hooke constant, friction coefficient). To apply specific physical phenomena on a particle system physically based operators has been implemented.

5.2. Description of the experiments

Two experiments were designed to assess the developed metrics of the applicability of shape modelers in collaborative conceptual design. In both experiments the following principles were followed that illustrate the cognitive model of the collaborative shape conceptualization process. First an idea is formed in the designer mind, which needs to be externalized. Then knowing the available software tools, the designer thinks about the way to generate the computer model of the idea. Finally, using the mouse and keyboard the designer generates and executes system commands that results in the model of the idea. To be able to compare the generated shape models by different designer, the initial idea has to be the same. Therefore, by neglecting the first step, each designer received picture of existing artifacts that had to be reconstructed in both experiments. In the first experiment, the task of the users of the system was to reconstruct the shape of a computer mouse shown in Fig. 5a. With this experiment we measured the speed of externalization and the similarity of the shape to the target shape of the mouse, which reflects the mental image of the designer and the shape that has been created in conceptual design system. The initial model, the designer started with, was a vague shape representing the global features of the mouse. Fig. 5b shows the vague model of the computer mouse. To generate the target shape, the users were supposed to apply compound instantiation on the

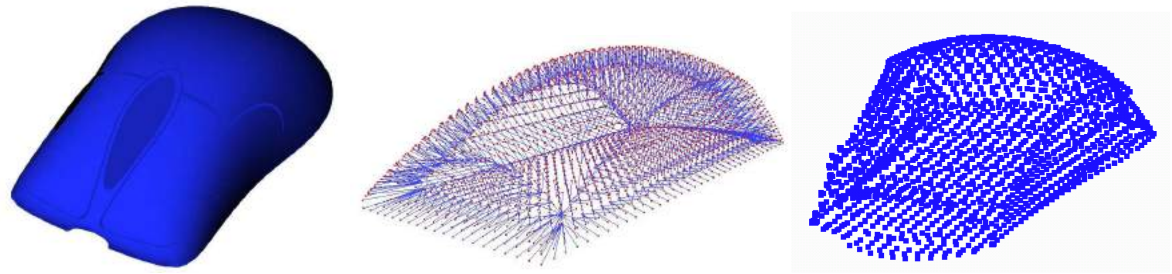

(a) target shape (b) vague model (c) result

Fig. 5. Shape models of the computer mouse

model. First, the regions of instantiation were specified by applying dynamic selection. For each region different instantiation functions were specified by the application of simple instantiation rules. The reference point of the instantiation function was interactively positioned for each region.

In the second experiment, two popular designs of chairs have been reproduced both by a conventional CAD system and by VDIM. This experiment focused on measuring the methodological enhancement introduced by the application of VDIM in conceptual design. Since VDIM applies a different design methodology compared to designing with conventional CAD systems, it makes sense to compare the two approaches. Designing with conventional CAD systems requires precise definition of shapes, and targets the creation of the final result rather than facilitating the development of evolving alternatives. In the case of VDIM, the process starts with creation of a rough global shape, which is modified in the course of instantiation. The productivity of the two approaches can be compared by measuring the time spent on creating a final shape or a set of shapes. Assuming that the model created by conventional CAD is accurate, the shape generated in VDIM is evaluated from the aspect of local morphological similarity.

5.3. Results of the experiments

Six users participated in this experiment. Fig. 5c shows one of the results that was produced by a user of the VDIM system. Since the local structural and curvature dissimilarity showed a significant difference between the generated shapes, only these two components of the feature vectors has been compared in Fig. 6. The charts show that none of the reconstructed shapes relative to the target shape is in the category of 'dissimilarity'. One of them was 'comparable', and three of them were 'similar'. Two shapes were found to be equivalent to the target shape. The total time spent on externalizing the model, t_e, was in the domain of [135..260] seconds. t_e is composed of the time needed to complete instantiation of regions and the time required to set the parameters of the instantiation function for each domain individually. Typically the users identified 4-6 instantiation regions. This means the time to describe a surface, t_{es}, on the object was between 10-30 seconds. Comparing this result to requirements, we can see that t_{es} approximates from above to the targeted domain. This result could be further improved by using advanced input means (e.g. hand gloves, and voice control) instead of the conventional GUI interface.

In the second experiment, users were asked to remodel the chairs shown in Fig. 7a. As a conventional surface modeler Rhinoceros 1.1 was used. To produce the left

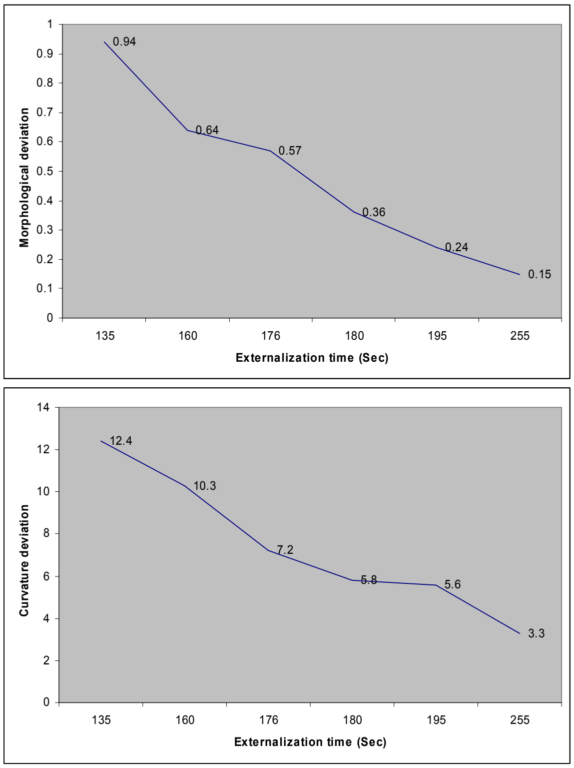


Fig. 6. Deviation of the designed shapes from the shape in Fig. 5

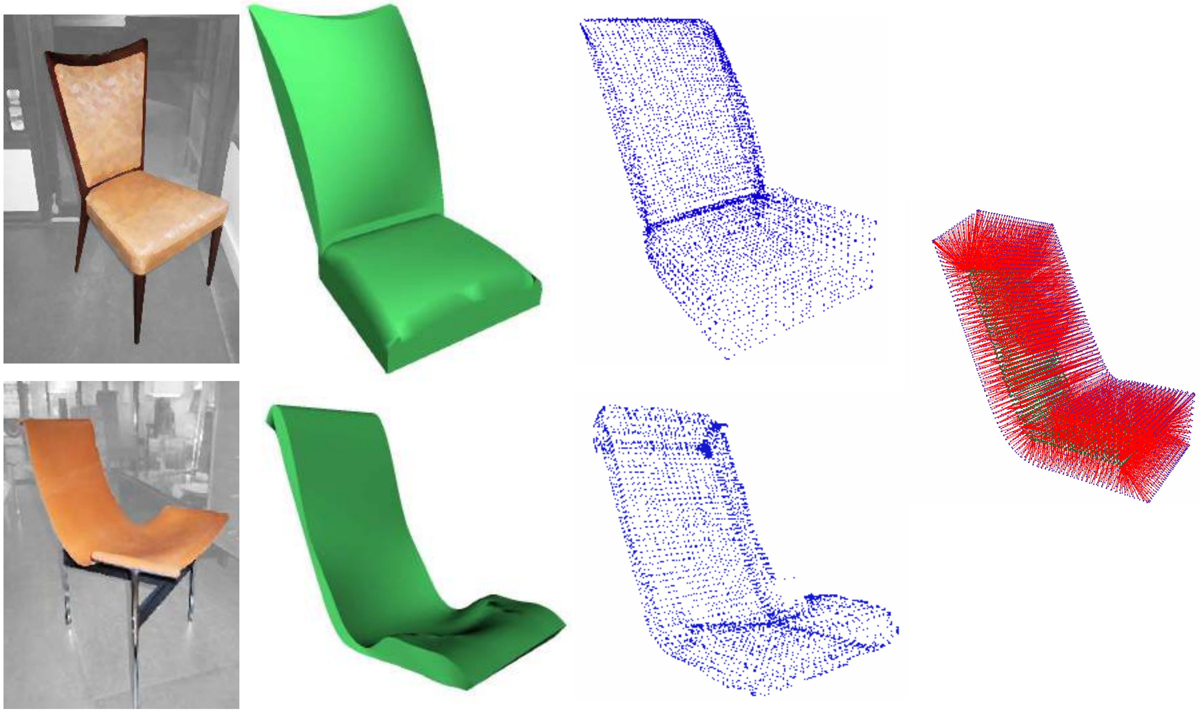
conventional CAD	t_e [min]	t [min]
left model	18	29
right model	15	36
both models	33	65

VDIM	t_e [min]	t [min]
vague model	5	15
region selection	7	20
instantiation of left	3	9
instantiation of right	4	11
left model	15	44
right model	16	46
both models	19	55

Tab. 1. Comparison of times spent on remodeling by Conventional CAD and VDIM.

shape 29 minutes were spent including 20 minutes externalization time. The surfaces were produced by rail sweeping the characteristic curves of a given surface and by joining the results together. Finally, the edges were filleted. In the case of the right shape, 36 minutes were spent including 15 minutes externalization time. Surfaces of this shape were produced by lofting cross section curves. Fig. 7b shows the resulting shapes.

To produce the targeted shapes with VDIM, first a vague model was created as a composition of planar point-sets. The vague model had to be carefully chosen to be able to derive both shapes from it. This required generating a large interval. This part of the exercise took 15 minutes including 5 minutes externalization. Next, regions representing all features of both the shapes have been selected. Selection of regions took 20 minutes including 7 minutes externalization. To derive the instance shapes, shape formation rules of curving, offsetting, and tilting were applied to each region. To instantiate the left shape took 9 minutes including 3 minutes externalization and instantiation of the right shape was 11 minutes with 4 minutes externalization. Tab. 1 compares the times used for remodeling the shapes by conventional CAD and VDIM. In the case when the models had to be individually created, conventional CAD was more efficient than VDIM. However, when for both models the same vague model and the same set of regions were used VDIM overcame conventional CAD system. Creating both models took 55 minutes by VDIM and 65 by conventional CAD system. Fig. 7c shows the resulting shapes generated by VDIM.



(a) targeted shapes (b) results generated by Rhinoceros 1.1 (c) results generated by VDIM (d) vague model of the chair

Fig. 7. Remodeling of chairs with conventional CAD system and with VDIM

6 CONCLUSIONS

This paper introduced a new benchmarking method to evaluate shape modelers from the aspect of their applicability in collaborative conceptual design. By investigating the cognitive model of collaborative conceptual design, three evaluation criteria have been identified: speed of externalization, expressiveness, and variability. To quantify these criteria, metrics has been established by integrating two approaches of shape similarity measures i.e. feature vectors and shape distribution. The authors presented two experiments in which an academic software package was compared to a commercial package. First the academic package was tested against the requirements of collaborative conceptual design that has been established based on a cognitive model. In the second experiment the academic and commercial package were compared by doing the same design task and evaluating the results. It has been found that there is no significant difference between the two packages, unless the design task is to generate several alternative solutions. By applying quantitative measures to evaluate shape modelers, it is easy to identify strong and weak points of a given system for a specific design task. As a general conclusion we can claim that the introduced quantitative measurement of indices proved to be useful to the assessment of applicability of various shape modelers in collaborative conceptual design. Furthermore, these indices can also be used to assess arbitrary systems, and conventional or emerging modeling techniques based on the criteria originating in the concerned application fields.

7 REFERENCES

[1] Ankerst M, Kastenmüller G, Kriegel HP, Seidl T. 3D shape histograms for similarity search and classification in spatial databases. Proceedings of 6th Symposium on Large Spatial Databases, 1999, p. 207-26.

[2] Chan S, Wong M, Ng V. Collaborative solid modeling on the WWW. Proceedings of the ACM Symposium on Applied Computing, 1999. p. 598-602.

[3] Craig DL, Zimring C. Support of collaborative design reasoning in shared virtual spaces. Automation in construction, 2002, 11(2): 249-259.

[4] Cybenko G, Bhasin A, Cohen K. Pattern recognition of 3d CAD objects. Smart Engineering Systems Design, 1:1-13.

[5] Dörner D. Approaching design thinking research. Design Studies, 1999. 20(5): 407-15.

[6] Elad M, Tal A, Ar S. Content based retrieval of VRML objects- an iterative and interactive approach. Eurographics Multimedia Workshop, 2001, p. 97-108.

[7] Garner S. Comparing graphic actions between remote and proximal design teams. Design Studies, 2001, 22(4): 365-76.

[8] Horváth I, Tromp N, Daalhuizen J. Comprehending a hand motion language in shape conceptualization. 2003, ASME-DETC-CIE-123, 2003, p. 1-16.

[9] Iyer N, Kalyanaraman Y, Lou K, Jayanti S, Ramani K. A reconfigurable 3D engineering shape search system part I: shape representation. ASME-DETC-CIE-48180, 2003, p. 1-10.

[10] Loncaric S. A survey of shape analysis techniques. Pattern Recognition, 1998, 31(8): 983-1001

[11] Madanshetty SI. Cognitive basis for conceptual design. Research in Engineering Design, 1995. 7(4): 232-40.

[12] Maher ML. Variations on a Virtual Design Studio. Proceedings of Fourth International Workshop on CSCW in Design, 1999, p. 159-65.

[13] Newell FN, Bülthoff HH. Categorical perception of familiar objects. Cognition, 2002, 85(2):113–143.

[14] Osada R, Funkhouser T, Chazelle B, Dobkin D. Matching 3d models with shape distributions. International Conference on Shape Modeling and Applications. ACM SIGGRAPH, the Computer Graphics Society and EUROGRAPHICS, IEEE Computer Society Press, Genova, Italy, May 7-11 2001, p. 154-166.

[15] Oxman R. Design by re-representation: a model of visual reasoning in design. Design Studies, 1997, 18(4): 329-47.

[16] Prasad B, Wang FJ, Deng JT. Towards a computer-supported cooperative environment for concurrent engineering. Concurrent Engineering: Research and Applications 1997. 5(3): 233–252.

[17] Rusák Z. Vague Discrete Interval Modeling for Product Conceptualization in Collaborative Virtual Design Environments. , Delft: Millpress, Ph.D. thesis, 2003.

[18] Saad M, Maher ML. Shared understanding in computer supported collaborative design. Computer-Aided Design, 1996. 28(3): 183-92.

[19] Scrivener SAR. Uncertainty and sketching behavior. Design Studies, 2000. 21(5): 465-81.

[20] Tovey M. Styling and design: intuition and analysis in industrial design. Design Studies, 1997, 18(1): 5-31.

[21] Verstijnen IM. Sketches of creative discovery: a psychological inquiry into the role of imaginary and sketching in creative discovery. Delft: DUT, PhD Thesis, 1997.