VISUAL SENSITIVITY ANALYSIS OF PARAMETRIC DESIGN MODELS

Improving agility in design

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ABSTRACT: The advances of generative and parametric CAD tools have enabled designers to create designs representations that are responsive, adoptable and flexible. However, the complexity of the models and limitation of human-visual systems posed challenges in effectively utilizing them for sensitivity analysis. In this prototyping study, we propose a method that aims at reduction of these challenges. The method proposes to improve visually analysing sensitivity of a design model to changes. It adapts Model-View-Controller approach in software design to decouple control and visualization features from the design model while providing interfaces between them through parametric associations. The case studies is presented to demonstrate applicability and limitation of the method.

KEYWORDS: Parametric modeling, visual analytics, sensitivity analysis, design

RÉSUMÉ : Les avancées des outils paramétriques et génératifs en CAO ont permis aux concepteurs de créer des représentations de designs sensibles, adaptables et flexibles. Cependant, la complexité des modèles et les limites des systèmes visuels humains ont posé des défis pour leur emploi effectif dans un contexte d'analyse sensitive. Dans cette étude, nous proposons une méthode qui vise la réduction de ces défis par l'amélioration de la sensibilité visuelle vers les changements d'un modèle. Elle adapte l'approche de « modèle-vue-contrôleur », empruntée du design de logiciels, pour interfacer des caractéristiques de contrôle et de visualisation par des associations paramétriques. Une étude de cas démontre l'applicabilité et les limites de la méthode.

MOTS-CLÉS : Modélisation paramétrique, analyse visuelle, analyse de sensitivité, design

1. INTRODUCTION

Parametric CAD systems can support change-control on design models to a certain degree and mainly through and on the model itself. Although they provide powerful modeling functions, they are weak for facilitating and visualizing sensitivity of a model to changes. For example, interaction occurs only on a design model, which is not sufficient alone to perceive the global or local effects of a change introduced. In this paper we present a prototyping study to formalize the process of change-control on parametric design models, and with a particular focus on geometric dependencies. The study combines visual analytics and sensitivity analysis (SA) approaches for achieving the following objectives:

- To augment designer's control on changing parameters while maintaining a parametric design-model's integrity.
- To provide interactive visualization means that can focus on different aspects (perspectives) of the model under change for insight gaining.
- To provide continuous feedback to support a change-analyze cycle and to enhance design cognition, visual search, and decision-making.

The approach to SA in this study differs from the conventional use of mathematical or statistical methods[1]. It rather falls in the visual (or graphical) sensitivity methods category such that the sensitivity of the model is controlled and displayed visually to the designer through interactive representations, which could be of same or different type than the model itself. The designer can interact with the visualization and control parametric variations of the model simultaneously. A parametric Bezier curve modeled in Generative Components (GC) is shown in Figure 1.

Visual analytics, on the other hand, enhances *insight gaining* and improves human-visual performance and (design) decision-making (Thomas *et al.* 2008). We propose a set of reusable and extendible perspectives to a design model to control and visualize changes decoupled from the model. We believe that these can enhance designer's perception of input-output dependencies during SA. The goal of using various change control and visualization perspectives is to alleviate the limitations posed by designer's visio-spatial memory (Ware 2004) such as change blindness (Simons 1996; Rensink 2005), visual attention (both locus and span) (Itti *et al.* 1998; Wolfe 2000), and visual search (Geisler and Chou 1995). It is also envisioned that these can reduce redundant navigation and zooming of the model and allow designers to focus on the task at hand rather than working around the application-specific view control features (Ware 2008).

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1. Refer to Ascough *et al.* (2005) for a detail description of sensitivity methods.

FIGURE 1. *A BEZIER CURVE IS CHANGED BY TWO CONTROL POINTS AND THE CHANGE IS VISUALIZED ON THE MODEL, ON A CIRCLE, AND ON A LINE AS VECTOR FIELDS.*
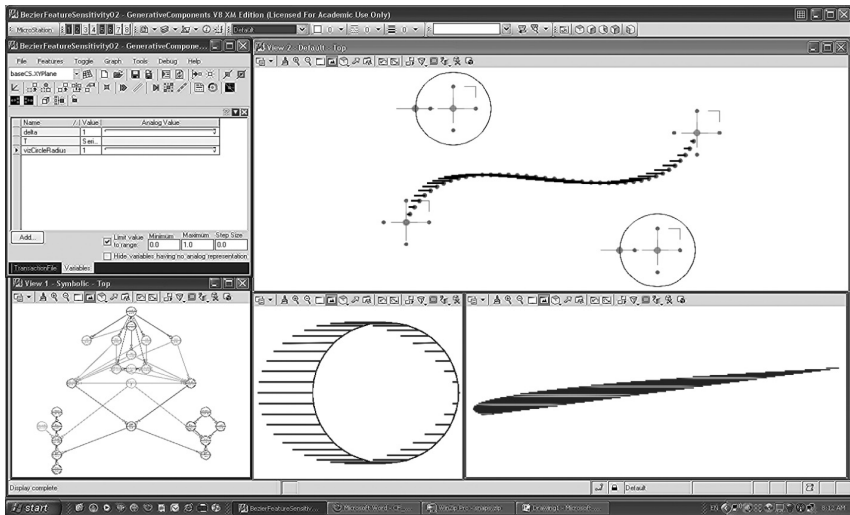
The next section briefly covers the foundations of this research, namely parametric modeling, sensitivity analysis, and visualization. Section 3 follows this by a description of the prototyping method proposed. The case studies are presented in Section 4 to demonstrate how the proposed prototyping method for SA can be applied on simple design models. Finally, the conclusions section discusses the initial outcome of this study.

## 2. DESIGN, VISUALIZATION, AND ANALYSIS

The study presented is situated in three main research domains: parametric (design) modeling, SA, and interactive visualization to improve human-visual system for performing the tasks in SA. Following provides an overview of these research areas in relation to the research presented.

2.1. Parametric systems and design

The research on design space exploration has gained more attention in the recent years with the emergence of advanced parametric design systems such as GC and Catia (Aish and Woodbury 2005; Hernandez 2006). These design systems with generative nature have become a "source of inspiration" for designers particularly when the "beauty" and "efficiency" of the model is also desirable (Kolatan 2006) (Figure 2). They are capable of creating, managing, and organizing of highly complex design models by defining design parametrically and searching for alternative solutions rapidly (Aish and Woodbury 2005; Qian 2007).

Parametric systems are different than conventional CAD tools: they are adoptable and responsive (Kolatan 2006). Their responsiveness is defined as reaction to applied changes and updating models in a real time basis. This is simply a 'rubber band effect': if the band is pulled from two ends, all the points on the band will respond to this change. Similarly, the geometric parameters of a model either trigger change or are modified to follow other changes such that the model is kept as a coherent structure by not losing its defined characteristics: it adopts the changes. These systems allow designer to create a range of the possible "sketches" of a single design model without a need to set up the models again from scratch (Hernandez 2006).

FIGURE 2. *HOK & BURO HAPPOLD LANSDOWNE ROAD STADIUM, DUBLIN (LEFT) AND TVSDESIGN, DUBAI TOWERS, DUBAI (RIGHT). (WWW.BENTLEY.COM)*
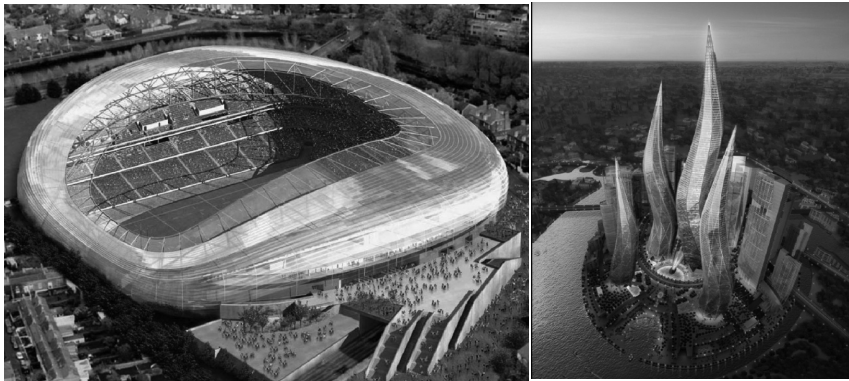
Defining design models and searching for a satisfactory solution manually or by employing conventional CAD tools can be quite costly and time consuming particularly for designs with complex geometries composed of curves and non-orthogonal folded planes. Designers make different versions of the model several times, and maybe from scratch to compare one solution to another in a discrete manner. The new generation CAD tools are more flexible. They, on the other hand, can eliminate or reduce the need for reproduction of the design models when a change is needed. Once a model defined changing parametric values can quickly generate variations in design; and if properly defined, models can respond to changes by propagating change to the associated elements in the design geometry.

Although parametric systems bring advantages to design, they pose challenges as well. The complexity of the design models increases parallel to the increased dependencies between design elements. At the task-level, particularly performing change on these models becomes hard to perform. The invisibility of dependencies, control and precision, frequently required view manipulations are some of the factors that contribute to the difficulty in using these tools.

Comparison of design variations is discrete and requires switching between projection views numerous times. Given the complexity of design geometries, designers change the model; observe the effects of the change by switching between different views; and assess consequences of change before selecting the next action. This intensely tool-specific cycle hinders particularly SA. Designers need new methods to enhance their perception for predicting the alterations in the design model without changing the reference model itself (Bates 2007). Regardless of these, the means to overcome the challenges exist in these systems' capabilities, such as reusable features, modularity, end-user programming.

## 2.2. SA in parametric modeling and CAD

SA can be defined as a study of the effects of a change in inputs on output of a model of a system (Frey *et al.* 2004)[2]. The term sensitivity in this study refers to the measure of change in one or more elements of a parametric design model when a change is applied in input parameters such as control points. SA in exploring parametric design models helps the designer to perceive the behavior of model, the coherence between parameters as well as interaction between them (Gill et al 1981); hence helps designers to make informed decisions in evaluating alternatives (Fraedrich and Goldberg 2000; Kleijnen and Sargent 2000). Generally, these decisions are "not only the most important task for designers but also mostly are the very difficult ones" (Arsham 2003). SA is mainly employed in design process in order to determine the following (Saltelli *et al.* 2000):

- Significant parameters that contribute the most output variability.
- Insignificant parameters that can be held constant or ignored.
- Whether there is interaction between parameters of design model or not? If so, which group of parameters interacts with each other?

For the CAD-based SA, the point of parameterization is "to characterize the change in dimensions and displacement of control points" (Hardee *et al.* 1999) which design model is defined by those control points (Figure 3). In exploring alternative design solutions mostly the perturbed input variable is selected from the control points that derives the geometry of design model (Braibant and Fleury 1984; Choi and Chang 1994).

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2. A detailed discussion of sensitivity analysis is out of the scope of this paper. The readers can refer to Ascough *et al.* (2005) for a general description of mathematical, statistical and graphical sensitivity analysis methods and to Saltelli *et al.* (2004) for applications.

FIGURE 3. *A BEZIER-CURVE WITH CONTROL POINTS P_{00}- P_{03} USED TO CREATE A PARAMETRIC ROOF SURFACE IN GC, WHICH RESPONSES TO THE CHANGES ON THESE POINTS.*
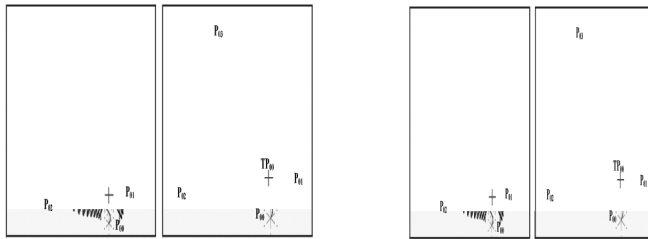
Increasing complexity of the models requires additional techniques to augment designers' control and perception of change to predict the behavior of a design model during SA. In the course of the change, the original model itself changes; therefore designers become restricted to what they remember from the earlier states, and are not able to track the effects of the change. This is mainly because the new variations can't be (computationally) compared to the earlier states of the model unless the previous model has saved intermittently. These drawbacks become more emphasized when the designer's visio-spatial cognitive limitations are considered.

2.3. Limitations in visual cognition in relation to visual SA

Visualization becomes as an extension to the designer's cognitive ability (Bertoline *et al.* 1995; Chandrasekaran 2004). It provides representations for concepts, and reveals relationships between concepts as spatial structures. Visual SA of a design model requires constant attention on the model during both changing and observing the effects of the change. Analysis also entails frequent switches from one representation to another and navigating in a model following change-observe-manipulate cycle.

We observe similar type of visually intense activities to visual SA studied in the human cognition research. The findings reveal the limitations of human-visual systems that also, we believe, apply to visual SA. The first significant limitation is the "change blindness" (Simons 1996) which is described by Rensink (2005) as "the inability to notice changes that occur in clear view of the observer (designer), even when these changes are large and the observer knows they will occur". The main goal in visual SA is to gain insight about the behavior of a model under change for agile analysis. However due to this limitation it is highly possible that the designer misses to observe the global or local change effects. The second limitation is related to the resources in visual memory: when external visualization of a model is not capable of representing the difference between pre- and post-change information clearly, designers make use of their internal representations. However, these are not accurate and more importantly subject to the limitations of visio-spatial working memory.

In visual SA, 'change' dynamically occurs and may or may not result with a directly observable outcome due to the magnitude or location of the change, or the zoom-factor of the view. Observing a dynamic change—as opposed to 'intermittent' changes (Ware 2004)—is restricted by the visual working memory's capacity of tracking 3-4 objects at a time. This impedes recognizing important changes on a large model (Rensink 2005). The designers need to maintain the continuity of the location and time of the elements being changed, which require proper support for effectiveness.

The complexity of a parametric model entails frequent view-manipulation (such as rotation, panning, filtering, zooming etc.) to analyze where and what change occurred, some of which can be obscured in the current view by the other parts of the model. However, at the task-level, this becomes a challenge for the visual system as this involves rapid shift in locus of attention and intense active scan (visual search) to gain insight about the model's behavior (Simons and Mitroff 2001; Geisler and Chou 1995; Walther 2006). The interpretation of changes involves taking visio-spatial information and then transferring them to spatial representations in order to make change more comprehensible (Zhan 2002).

The following section describes how visual analytics can help in addressing these issues in the context of the prototyping method we propose.

2.4. Visual analytics: improving interaction during SA

In order to tackle the challenges mentioned for CAD-based visual-SA, we propose to utilize visual analytics techniques. Visual analytics provides methods that leverage the human visual cognition through human-centered interactive systems to support the process of decision-making (Thomas and Cook 2005). Our approach to visual analytics includes controlling and viewing sensitivity of parametric design model through visual, dynamic, and interactive representations to improve the performance and comprehension.

The VA methods define the process of task-performance by visualization means. For example during the interaction between (design) visualization and the user, three main loops occur (Ware 2004). At the low-level loop: designer interacts with objects by selecting and moving using "eye-hand" coordination. At the intermediate level loop, the exploration, navigation, and view refinement take place. The higher-level loop includes problem solving, where the observer forms hypotheses about (design) data and refines them through augmented visualization process. These loop cycles are revised and replaced accordingly as new data added.

The tasks related to the visual SA will benefit from the visual design principle of applying multiple views of a design model ("windows" in Ware's terms) rather than zooming and view manipulation to reduce "visual complexity" (Ware 2004). We propose to utilize multiple visualizations (both for paramet-

ric controls and views) generated from the parametric model to be interacted
with when analyzing sensitivity. Following section describe the method in detail
by presenting case studies.

3. PROTOTYPING METHOD FOR VISUAL SA OF PARAMETRIC DESIGN MODELS

SA is essentially an experimental activity on the design model for implement-
ing 'what-if' scenarios. It is also utilized in design exploration when there is
uncertainty about how design form could change upon changes on (critical)
control points. However, the limitations of the parametric tools combined with
the limitation of the human visual system hampers the process. The goal of the
method is to achieve better change control on the model and improved change
representation.

3.1. Introduction of the method

The overall structure of the method comprises 'model preparation', 'selection
and initiation of visualization' and 'analysis' phases. In first phase, design mod-
els are linked with controllers. In the second phase visualization means are
strategically associated with controllers and models. The analysis of a model
is conducted through a change-analyze cycle comprising of four distinct tasks:
introducing a change on controllers, switching focus between controls and
visualizations, observing, and assessing the change effects (Figure 4).

FIGURE 4. *PROCESS MODEL FOR CONDUCTING VISUAL SA.*
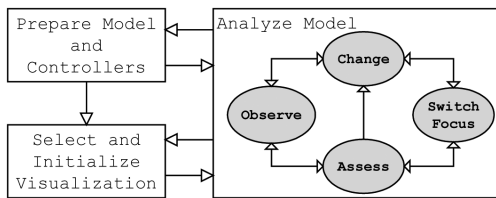
The method is iterative and uses a structural model inspired from the
Model-View-Controller framework in software design (Burbeck 1992). The
idea is to decouple visualization and controllers from the design model so that
the model can contain only design-relevant information (Figure 5) 'Features'
are composed of geometric objects. The parameters of these objects can be
linked to existing objects to receive input; or they can derive values of other
parameters in other objects. This capability enables creation of reusable features
at different levels that can interface with each other through their constituent
objects.

FIGURE 5. *STRUCTURAL MODEL DECOUPLING MODEL FROM VIEW AND CONTROLLERS.*
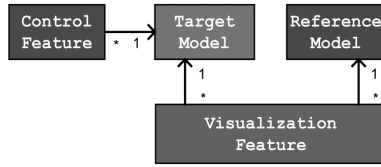
3.2. Model preparation: controls and clones

As noted, in this phase, the Reference Model (RM)—the original design model—is cloned as a Target Model (TM), and a set of Control Features (CF) is associated to the TM and RM. The purpose in this is to keep the RM intact while applying and comparing the changes on the TM. The CF is used to control the parameters on the TM which sensitivity of the model to their change is of interest (Figure 6). For example the CF shown in Figure 7, P_{01} and P_{02} are defined as part of the original Bezier curve (RM) and reused as reference points for creating the CFs.

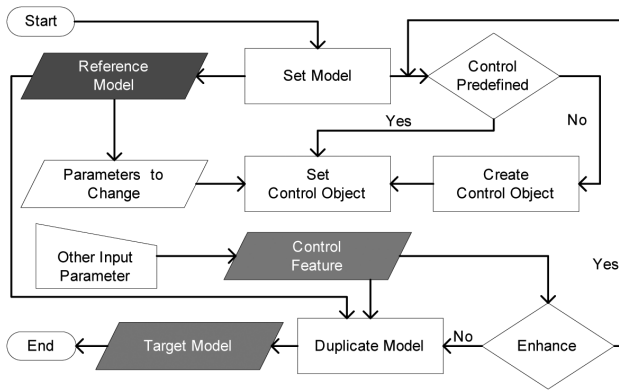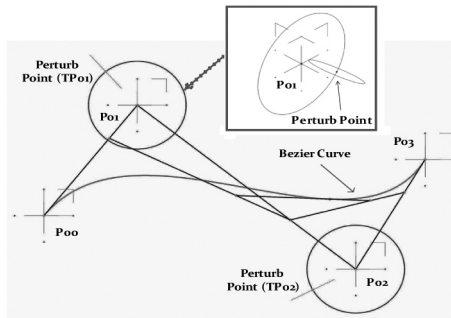**FIGURE 6.** *PREPARATION PHASE ACTIVITY DIAGRAM.*

FIGURE 7. *CURVATURE-DISTANCE CONTROLLER COMPOSED OF A CIRCLE AND A PERTURB POINT. TWO INSTANCES ARE ASSIGNED TO A BEZIER CURVE'S CONTROL POINTS P_{01} AND P_{02}.*

RMs are kept unchanged as benchmark models to compare them computationally to their clones (TMs) on which changes are performed. Note that a TM as a 'clone' of an RM does not mean a one-to-one copy: in creating a TM, the objects in an RM are reused except the ones that their influence on sensitivity is of interest. They are duplicated and associated with objects in the CFs. The Perturb Point TP_{01} is an example of this type of objects. In addition, the visibility can be toggled: in Figure 7, the clone Bezier curve TM is hidden from the view intentionally for a better control.

3.3. Selection and initiation of visualization

In the second phase a set of Visualization Features (VF) are associated with both RM and TM. Their role is to continuously calculate the changes and visually inform the designer of sensitivity of the model to changes, i.e. display output from the model. The structure may include one or many CF and VF associated with the design models. The responsibility of the VFs is to reveal changes, again visually and interactively. Unlike CFs, a VF is associated with both RM and TM to receive input from both models to calculate and visualize the change (Figure 8). They are interfaced with the models, again, through the objects defining the both models. VFs should be strategically selected and assigned to focus on particular locations that change is of interest. As well as using 'on model' VFs, they can also be displayed independently from the models (see Section 4.1).

FIGURE 8. *VISUALIZATION FEATURES SELECTION AND DEFINITION ACTIVITY DIAGRAM.*
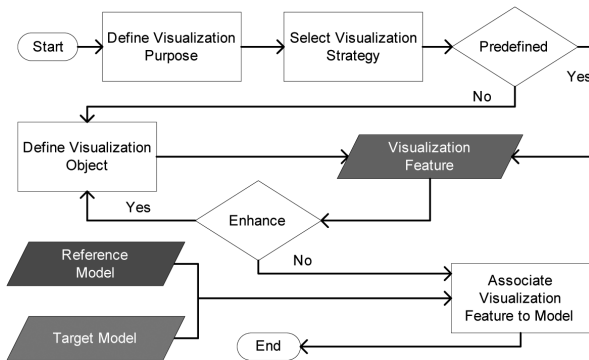

3.4. Analysis of design model using CFs and VFs

Visual SA process proposed in this study is iterative. Following the choices on the parameters to be studied, the location of the expected changes, and selection of appropriate visualization means, the designer starts the analysis process. While the CFs provides 'precision control' on input, the VFs dynamically and in real-

time calculates changes in the TM relative the RM, and visualize these changes as specified in the VFs internal structure. The process can start either by focusing on CFs or VFs. As needed, the designers can introduce new CFs or VFs; or can refine parametric associations. These require revisiting the 'model preparation' and 'selection and initialization of visualization' phases. Otherwise, the change-observe-assess cycle continues as described (Figure 9).

FIGURE 9. *VISUALIZATION FEATURES SELECTION AND DEFINITION ACTIVITY DIAGRAM.*
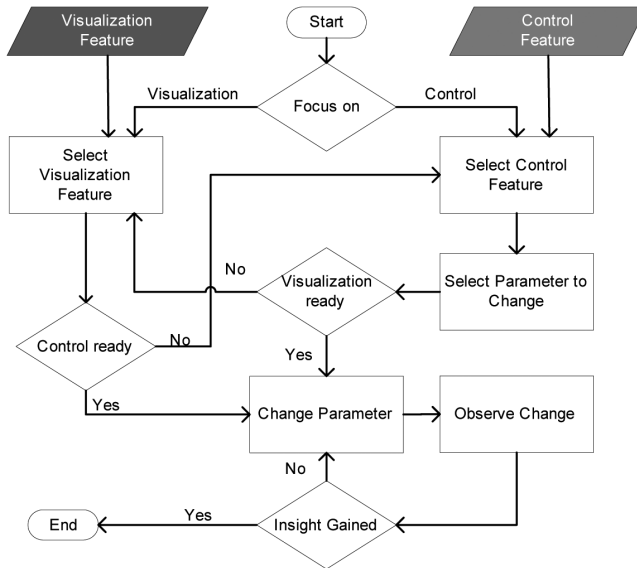

4. CASE STUDIES

We have conducted several case studies to evaluate and verify the applicability of the method. Some of the models tested are Bezier curve, B-Spline Surface, Surface overlap and other problem-specific design models. Below we present two of these case studies. Due to the page limit and for the purpose of clarity, we selected relatively simple cases.

4.1. Bezier curve

Bezier curves are widely used in design and computer graphics. We choose to work on a third order Bezier curve as 'design model' in the first case study. The curve is constructed using four control points (P_0-P_3) (Figure 7). Two Curvature-Distance CFs are associated with the TM and RM to change P_2 and P_3. The Reference Control Points of the CFs are linked to the points P_2 and P_3 in the TM. The Perturb Points TP_2 and TP_3 controls two parameters: *delta* and T. '*delta*' refers to the unit distance between the reference and the Perturb Point.

T is in the domain T ∈ [0, 1] and refers to the proportional distance along the curve between the starting and end points. The sensitivity of the RM is evaluated by changing *delta* and T.

FIGURE 10. *THE BEZIER CURVE'S CONTROL POINTS ASSOCIATED WITH TWO CURVATURE-DISTANCE CFS. THE CHANGE IS VISUALIZED ON FOUR DIFFERENT VFS.*
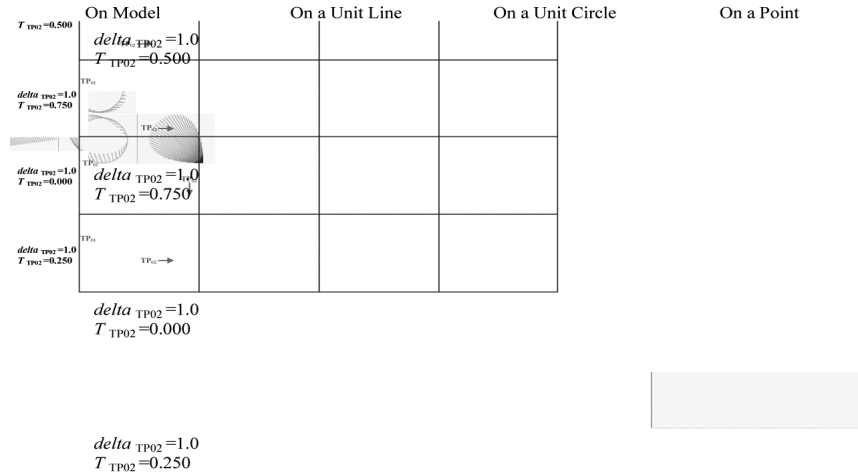

The analysis of the results shown as vector fields and reveals that the curve is highly sensitive to changes on the T value of the perturb point controlling P_{02} (Figure 10). The direction of vector fields moves dramatically as the T value changes by 0.5 unit. Although 'On Model' VF does not show this change, the other VFs visualize the change clearly.

4.2. B-Spline surface

In this case study we use a B-Spline surface defined by P_{01} - P_{06} control points and represented by a quadrangular-meshed net (Figure 11). The focus of sensitivity is the elongation on the surface meshed-components when P_{03}, P_{04} and P_{06} are displaced. In order to control the displacement, we reused the Curvature-Distance Controller. The sensitivity is visualized by Circle-Size VFs located on the edges of the net that their radiuses visualize the elongation value by comparing the RM to the TM. Again, the TM in this case study set invisible to prevent image clutter and improve perception.

FIGURE 11. *A B-SPLINE SURFACE WITH SIX CONTROL POINTS AS QUADRANGULAR-MESHED NET. SENSITIVITY ANALYSIS OF THE B-SPLINE SURFACE TO THE CHANGES ON P_{03}, P_{04} AND P_{06}.*
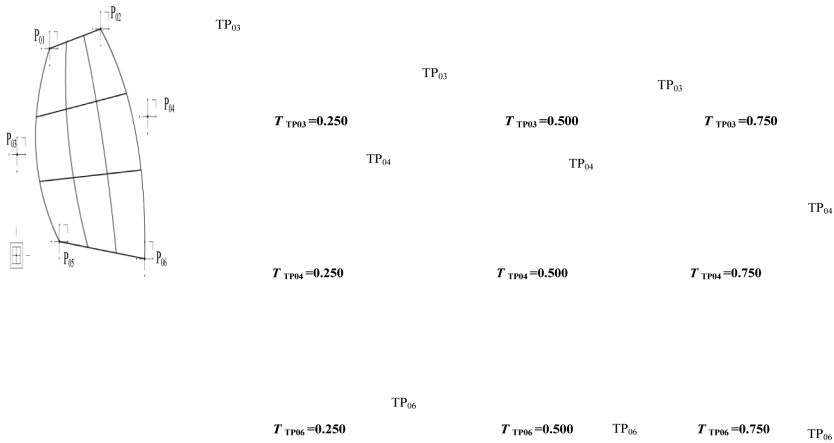
The result of the analysis reveals that the edges of the net tend to elongate more when P_{03}'s T value changed; and most of the elongation takes place in the mesh's middle zone (top-center figure in Figure 11).

5. CONCLUSIONS

The use of visual analytics in SA on parametric modeling was emphasized in this study. There are some conventional methods currently in use in computing SA but they cover the overall aspects of SA without any explicit enhancing in the control and perception of change effects on parametric design-models. In particular the introduced method is a complete framing for computing SA and applied cognitive techniques to answer designers' need for a successful design. Although the introduced method targets to improve designer's performance in perceiving and predicting the behavior of the parametric design model, there are some concerns with cloning the RM to create the TM in the preparation phase. The limitations rise mainly due to the increase in the complexity of the design model. As a partial solution a deep-copy feature, which requires an application-level programming, can be developed. In the case studies, the models were cloned by the use of object-copy and input-replication techniques. Although it is early to conclude the utility and effectiveness of the method in real-world use, the systematic approach introduced can help developing new features in the parametric systems for SA. Another challenge in the introduced method is that it is prone to loss of attention due to the possibility of very frequent 'switch-focus' actions. Again, visual analytics methods can provide better solution by contextualization of change visualization. While these solution techniques are not of the main focus; they are open for improvements.

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