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Influence of a hybrid digital toolset on the creative behaviors of designers in early-stage design

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ABSTRACT

The purpose of this research was to investigate how diversification of the repertoire of digital design techniques affects the creative behaviors of designers in the early design phases. The principal results of practice-based pilot experiments on the subject indicate three key properties of the hybrid digital tooling strategy. The strategy features intelligent human-machine integration, facilitating three different types of synergies between the designer and the digital media: human-dominated, machine-dominated, and a balanced human-machine collaboration. This strategy also boosts the cognitive behaviors of the designer by triggering divergent, transformative and convergent design activities and allowing for work on various abstraction levels. In addition, the strategy stimulates the explorative behaviors of the designer by encouraging the production of and interaction with a wide range of design representations, including physical and digital, dynamic and static objects. Thus, working with a broader range of digital modeling techniques can positively influence the creativity of designers in the early conception stages.

1. Background and motivation

In the context of applying technology in the processes of creation, research on how people interact with computers provides a relevant base for knowledge developments in the design disciplines (Carroll, 1997). Numerous studies on this subject indicate that computers positively affect the creative undertakings of designers (Candy & Hori, 2003; Chang, Chien, Lin, Chen, & Hsieh, 2016; Edmonds, 1994; Greene, 2002; Mitchell, 2003; Robertson & Radcliffe, 2009; Shneiderman, 2002). However, the available tools are considered unsatisfactory for aiding the initial stages of the creation process (Horváth, 2004; Lawson, 2005). Researchers have noted several features that hinder successful early design support.

The first is the prevalent focus of digital tools on the automation of conceptual design, while designers usually prefer to work intuitively in those stages. Although automation can be useful early on, especially for tasks that are cumbersome for human designers, it eliminates the possibility for creators to enter into deeper interactions with the design medium, which poses a large risk of restricting human creativity (Liu, Li, Li, & Pan, 2011; Oxman, 2000; Yin et al., 2015).

Another reason why digital systems do not perform well in early design is that they are unable to fully sustain the complexity of human design thinking (Lee, 2016; Liu, Chakrabarti, & Bligh, 2003). The design process is nonlinear, iterates over multiple loops of divergence and convergence, and the design concept is reworked multiple times, with designers often working back and forth to develop their ideas (Lawson, 2005). In contrast, most of the current digital design support systems offer standardized workflows based on linear or waterfall models of design (Horváth, 2004). If iteration takes place, it is most often a computer-performed process, in which the possibility of human intervention is minimal.

Finally, the critics of early-stage computer support of design argue that a single system is unable to aid the distinct cognitive phases of idea development. The early design process has several such phases including abstract concept creation, idea embodiment, and detailed design. The digital tools usually target one of those stages, most often detailed design (Islamoglu & Deger, 2015). In this setting, the role of the computer is that of a drawing tool, used for representing the finished designs rather than a medium aimed at stimulating creativity (Séquin, 2005).

One of the current research proposals intended to challenge the abovementioned shortcomings is the integration of distinct digital systems into hybrid design environments. These include synergies of Computer-Aided Design (CAD) systems with Computer-Aided Engineering (CAE) systems, CAD with Computer-Aided Manufacturing (CAM) systems, and CAD with Virtual Reality (VR) and

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Augmented Reality (AR) systems. Several studies within the area report positive effects of such mergers on designers' creative behaviors (Lee, 2016; Shea, Aish, & Gourtovaia, 2005; Stark, Israel, & Wöhler, 2010; Zboinska, 2015b).

In addition to the integration of distinct systems noted above, it has also been suggested that various 3D modeling methods within the CAD system could be used in the design process (Kolarevic, 2003; Oxman, 2006). However, there is little research on this type of integration. Although Oxman (2006) introduces a theoretical model for such a system, only an outline for the integration is provided. Further research is necessary to learn more about how this merging affects the human-machine relationship and the creative behaviors of designers. This yet-unexplored integrated model of digital design inspired the hereby presented study. It serves as a point of departure to construct and investigate a hybrid digital tooling platform, which may compensate for the imperfections of the early-stage digital design support systems outlined above.

The article is organized as follows. In Section 2, we present the theoretical foundations for our research and present a set of designer behaviors that we consider creative and relevant for this study, as well as the conceptual framework for constructing the hybrid digital toolset and a description of its components. In Section 3, we discuss the methods of our investigation and present the design experiments conducted. Section 4 presents the experimental results in relation to the creative behaviors presented in Section 2, discussing how the design process supported with the hybrid toolset differs from the analogical process typical for mainstream digital architectural practice. We close the article with Section 5 and present a broader outlook on the research.

2. Theory

2.1. Behaviors triggering creativity

To investigate whether and how the hybrid digital design toolset influences the behaviors of designers in early creation stages, we must characterize the behaviors of interest. In this study, we focus on the activities that can potentially compensate for the three shortcomings of digital design support systems outlined in the introduction. We study three types of behaviors: interactions between the designer and digital media, design thinking, and manners of design idea expression and exploration.

2.1.1. Interactions between the designer and digital media

Previous studies argue that successful digital design systems must feature intelligent human-machine integration (Yin et al., 2015). The designer should be able to seamlessly cooperate with the computer and both should fill in for each other's deficiencies. In that interaction setting, the computer performs quantitative tasks of computation and the designer is involved in qualitative activities related to intuition and cognition. This is believed to boost human creativity and alleviate designers from traditional burdens using computers (Lu & Chen, 1994).

Researchers also suggest that successful intelligent human-machine integration should take place in at least three configurations: human-dominated, machine-dominated and a balanced human-machine cooperation (Yong & Chen, 2000). Studies indicate that this three-fold character of interactions makes the integration even more robust because the different interaction types can be interchanged over the course of the design process so that each is applied to handle the design tasks it is most suitable for.

In sum, a successful digital design support system must allow for the designer to freely enter a variety of interactions with the digital media and use the power of human intuition and computation interchangeably and effectively.

2.1.2. Design thinking

Studies reveal that three kinds of design thinking activities typically occur in creative design: divergence, transformation and convergence (Jones, 1970). Divergence is the creation of multiple design solutions, transformation deals with refining these solutions and convergence is the selection of the final design. The presence of those stages and their progressive actuation leads to generation of creative design concepts (Cross, 1994; Pugh, 1991).

In the context of computer-aided creative design, recent studies suggest that nonlinear design workflows increase design creativity (Grobman, Yezioro, & Capeluto, 2010). That divergence, transformation and convergence should be carried out in several iterative cycles to guarantee that the design explorations are extensive enough to produce a meaningful final concept (Liu et al., 2003).

Successful creative digital design, which progresses through the abovementioned stages, should also enable the creation of design abstractions at all levels of concept development: global, local and detailed (Sarkar & Chakrabarti, 2007). The designer must be able to generate ideas on all those levels; in practice, this involves the creation and exploration of design spaces containing multiple design alternatives.

Consequently, a successful digital design support system should let designers behave according to the typical creative thinking cycles and embrace divergence, transformation and convergence to maximize the palette of their creative thinking behaviors. It must also allow for exploring design solution spaces at all levels of idea abstraction.

2.1.3. Behaviors linked to exploring and expressing ideas

Experimental psychologists argue that people use images, not descriptions, in their cognitive activities (Dreyfus & Dreyfus, 1986). Consequently, creative design can take place under the condition termed by cognitive psychologists as image-based thinking (Kellogg, 2002). That is, a person must be able to generate, analyze and interact with visual representations to be creative. The studies of cognition in design further claim that the visual and cognitive interactions between the designer and the visual representations propel creative idea development and trigger the emergence of innovative design solutions (Oxman, 2002). Moreover, it is argued that representations must be varied to stimulate creative thinking. Thus, they should involve both digital and physical design artifacts that the designer can visually and tangibly interact with (Lee, 2016). Furthermore, studies suggest that 3D representations that are dynamic add to the people's creativity (Chen, Hsiao, & She, 2015).

Thus, a successful digital design support system must facilitate the production of multiple and variegated design representations in digital and physical forms, preferably including dynamic ones, and allow for multisensory interaction with them.

2.2. Hybrid digital design toolset for a compound integrated model of digital design

Several features of Oxman (2006) compound integrated model of digital design are relevant for this study. First, the model assumes that the designer interacts with five different 3D modeling methods: formation, animation, parametric design, generative modeling and performative design. We see this design medium differentiation as an opportunity to fulfill the variegated creation needs of designers in the early conception phases. A second important feature of the model is that the designer remains at the center of the design process. We believe that this guarantees certain levels of control over the creation processes. Moreover, this feature of the model allows for the designer to steer how interactions with the digital media occur, and these interactions can have a varying character in terms of who dominates – the human, the computer, or both. Finally, it is vital that the model supports a variety of interplays between the designer, the digital media and design representations. This increases the chances for creativity to occur in the design process because the designer is presented with an opportunity to use those interplays for design explorations.

2.2.1. Framework components

Considering the above assumptions, we constructed a hybrid digital framework for explorative design. The framework structure is based on software supporting four different 3D modeling methods: freeform modeling, animation-based modeling, parametric design and algorithmic modeling. We added a fifth element to this structure: a CAM system that includes tools for rapid prototyping. This addition was motivated by the results of recent research on integrated CAD/CAM systems that argued that such a merger can broaden the range of creative behaviors of designers by supporting robust interactions with physical design representations derived through digital processes (Lee, 2016).

An overview of the design support abilities of the digital techniques in our hybrid platform is presented below.

The freeform modeling technique involves working in 3D modeling environments to facilitate the creation of complex surfaces and nonstandard geometries (Kolarevic, 2003). The design workflow is primarily manual. The designer constructs objects from scratch directly in the digital space. The technique offers a unique possibility to explore geometrically complex forms by freely manipulating them in 3D space (Kolarevic, 2003). The software that supports this technique in our platform includes Rhinoceros®, 3Ds Max® or Maya®.

The animation-based modeling technique employs 3D animation software that can simulate the reshaping of geometrical objects under the influence of external forces. It embraces working with time-based dynamic systems such as particle systems with applied forces. The design process is not focused on direct manual construction of 3D objects. Instead, the designer prepares input geometries for the computational transformations and establishes which types of dynamic systems will cause these transformations (Lynn, 1999). The unique creation opportunity offered by this technique is the possibility to work with relationships between objects and their deforming forces, which can aid the development of conceptual ideas behind the project (Rahim, 2006). Due to its partly automated character, it allows for determining unpredictable spatial effects, which is often appreciated by designers (Kolarevic, 2003). Software examples for our platform include 3Ds Max®, Maya®, Kangaroo Physics and FlexHopper.

The parametric design technique features the use of parametric modeling tools. Similar to animation, it does not focus on modeling the objects directly by hand and emphasizes the geometric and mathematical procedures of their generation by the computer (Woodbury, 2010). Qualitative and quantitative parameters used in these procedures define the process of digital formation of 3D objects. The unique opportunities for design offered by this technique allow for control of complex geometries from the bottom up, using the parametric generation instructions, and for easily producing design alternatives by altering the parameters that affect the shapes of objects (Aish, 2003). In our platform, we suggest the use of Grasshopper® software to facilitate this technique.

The algorithmic modeling technique is a 3D modeling method based on the use of mathematical algorithms applied within 3D modeling environments to create and alter geometries. Various algorithms can be used, including mesh subdivision algorithms and highly complex evolutionary systems such as genetic algorithms (Piacentino, 2013; Singh & Gu, 2012). The designer's role is to determine the input conditions for a predefined system or, if the design goal is to create the algorithm itself, invent that algorithm. Notably, the use of algorithms in this technique is not limited to their implementation. It also has strong conceptual implications linked to a digital design paradigm called algorithmic thinking (Terzidis, 2006). It involves focusing on the design artifacts and the computational processes leading to their creation (Runberger, 2012). The unique opportunity offered by this technique includes the possibility of conceptualizing and computationally managing the alteration of complex digital 3D constructs (Peters, 2013). In our experiment, we employ mesh modeling algorithms with the aid of a Grasshopper® plug-in Weaverbird but other add-ins can be used, including Kangaroo Physics (features dynamic relaxation algorithms), Octopus (supports genetic algorithms), or Rabbit (enables the use of cellular automata and L-system algorithms).

The rapid prototyping technique is a CAM technique. In this article, we focus on additive manufacturing enabled by 3D printers that produce 3D models from layers of a certain material. The designer provides input in the form of the object's digital model and the computer-controlled printer produces that object in physical form. The unique creation opportunities offered by this design medium enable rapid production of design prototypes, allowing for their mental and sensory examination in real space, and for the possibility of producing prototypes of complex and detailed architectural objects that would be difficult to make by hand (Sass & Oxman, 2006). The rapid prototyping systems involved in this study employ Fused Deposition Modeling (FDM) and Color Jet 3D Printing (CJP). By altering the parameters of the printing process, especially those involving FDM machines, the designer can significantly affect the esthetic appearance of the produced objects. This can be done using dedicated 3D printer software with access to the print configuration files, such as MakerWare™ for the MakerBot® printer or dedicated add-ins for Grasshopper® such as Silkworm.

2.2.2. Framework structure

In Fig. 1, we present a detailed diagram of the framework structure, with examples of existing software supporting the digital modeling and materialization methods described above and the types of user interfaces they should ideally feature. In Fig. 2, we

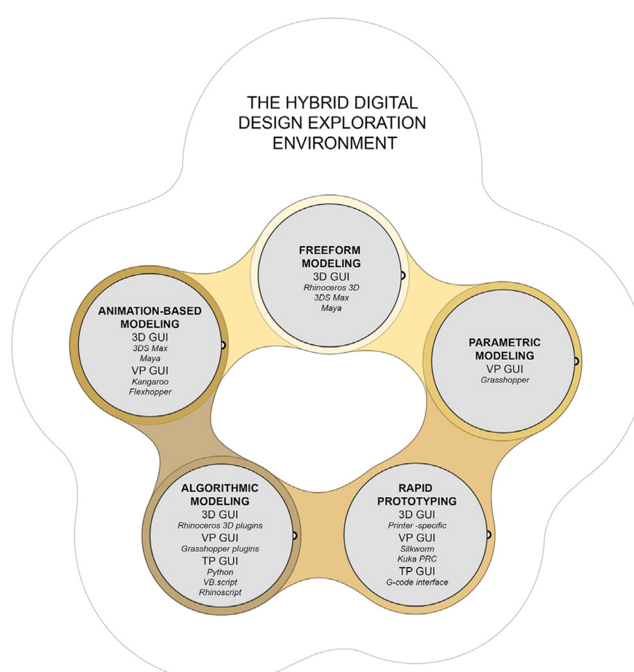

Fig. 1. Detailed diagram of the hybrid framework structure, with software examples and types of GUIs.

illustrate the multidirectional transitions between the tools in the platform. These are based on the idea that the designer can spontaneously switch from one technique to another at any time during the creation process based on current exploration needs. In Fig. 3, we present the various kinds of human-machine interactions between the designer and the techniques in the platform.

There are two basic alternatives for how our framework can be instantiated as a comprehensive software environment. The first option is to construct the platform from a variety of off-the-shelf 3D modeling environments that support freeform modeling, animation-based modeling, parametric design, algorithmic modeling and rapid prototyping. However, this option may pose some technical challenges to the user. Popular 3D modelers used in architectural design are based on differing geometry kernels, so there may be interoperability issues when employing them in a design process. We outlined the problematic issues in constructing such a platform in another article (Zboinska, 2015a).

In the second option, interoperability issues posed by geometry transfers between the various environments can be eliminated by using a common geometry kernel. In practice, this could mean a core 3D modeler together with a pool of add-ins that provide the functionalities of the different 3D modeling methods (freeform modeling, animation-based modeling, parametric design, algorithmic modeling, rapid prototyping). In this option, the different techniques are accessed by the user through a layered GUI built around a common geometry kernel (Fig. 4). The core of such an interface consists of a classic GUI, found in most 3D modelers, featuring a set of icons for the individual commands, a command line for inputs and scripting, and geometry view windows. This GUI comprises a visual display interface for all five modeling methods from the proposed hybrid toolset, allowing for geometry previews at all times from all interfaces. Floating on top of that interface is the visual programming interface (VPI), in the form of a window in which a flow-based programming can enable animation-based, parametric and algorithmic modeling. There should also be a third interface, i.e., a textual programming interface (TPI), geared towards more advanced, bottom-up algorithmic design. It should be possible to call it from the level of the core 3D GUI or the VPI. One geometry kernel linking all three interfaces enables all modeling work to be done conveniently in the same core environment. An example of an existing practical implementation of such a system is the Rhinoceros® 3D modeler with the Grasshopper® add-in as the VPI and the TPI interface for programming in a particular language such as Python™ or VB.NET. To enable various 3D modeling methods, dedicated add-ins for Grasshopper® are used, e.g., Kangaroo Physics for animation-based modeling, Weaverbird for algorithmic modeling and Silkworm for rapid prototyping control.

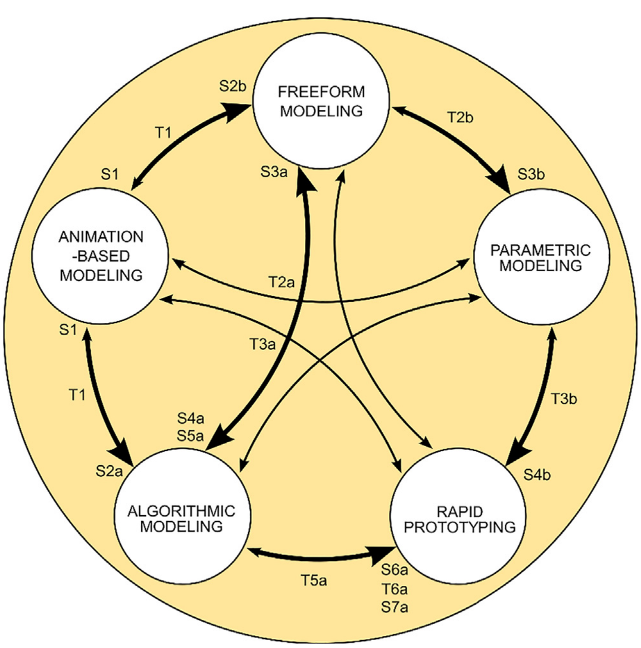

Fig. 2. Multidirectional transitions between the platform tools (stages and transitions for the research experiment are indicated with labels and thick arrows).

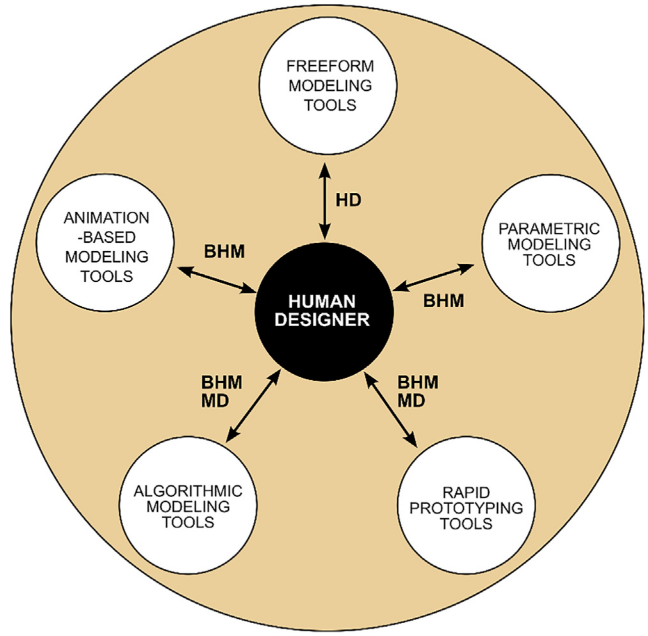

Fig. 3. Modes of human-machine interactions featured in the hybrid platform (HD = human-dominated mode; MD = machine-dominated mode; BHM = balanced human-machine mode).

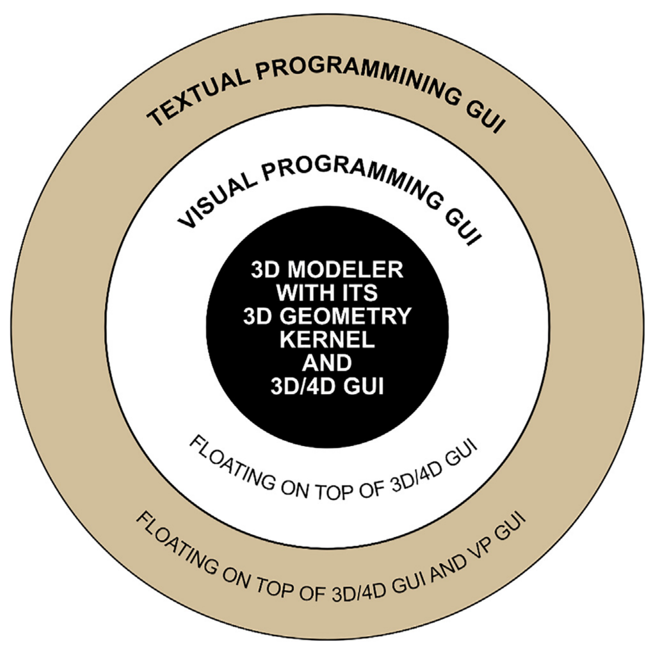

Fig. 4. Layered graphical user interface framework for the hybrid tooling environment.

3. Investigation method and implementation

We chose practice-based research as the most suitable investigation method for this study. This method is rooted in Schön's notion of reflective practice, in which the design process is perceived as a reflective conversation with the materials of a design situation (Schön, 1992). Following this line of thought, the practice-based research method focuses on observing how designers think and create and using those insights to develop new knowledge on design (Candy, 2011; Dunin-Woyseth & Nilsson, 2013). It often involves the staging of explorative design experiments, in which designers carry out certain creation tasks (Billger & Dyrssén, 2005). In the experiments, the design process is carefully observed and registered (Pedgley, 2007). This allows for gaining knowledge regarding how designers behave while designing under particular conditions – how they carry out their cognitive processes and how they engage with their physical and psychological raw materials (Dallow, 2003; Dyrssén, 2011). The experimental products include design protocols that capture designers' reflections and design artifacts that represent design concepts in drawings and models. These products form a basis for performing research analyses and drawing research conclusions (Candy & Edmonds, 2011; Scrivener, 2002; Sullivan, 2004).

In this research, four such design experiments are conducted using the hybrid digital design toolset applied to carry out the early conceptual design processes. One of these experiments, called *The Embodiments,* is selected for an in-depth analysis in this article, and the others are documented elsewhere (Zboinska, 2015a, 2015b). The goal of the presented experiment is to focus on the designer behaviors and observe if and how the hybrid toolset can steer the creative behaviors of the designer as each technique and human-machine interaction mode is incorporated in the digital creation process.

Based on the adopted research method, we use reflections from the design process and design artifacts produced in that process as research knowledge sources. Design protocols serve the purpose of registering the designer's reflections upon the digital creation process and help capture the behaviors of the designer. The architectural representations and artifacts arising from the experiment are also research evidence that help us assess the role of the hybrid toolset as a booster of the creative actions of the designer.

In the presented experiment, an architect designs architectural objects using the hybrid digital toolset. The design task is intentionally general to avoid limiting imaginative design with excessive specifications. The goal was to create a decorative interior space partition. The project was conceptual and meant to be treated as an early-stage architectural vision. It did not explore the detailed functional or structural properties of the object, rather its visual features – form, ornamentation and general esthetic appearance.

The design stages and transitions between the digital techniques in the experiment are shown in Fig. 2. The specific behaviors of the designer that arise in the course of the experiment are indicated in Fig. 5. The gradual development of the design concept, documented by selected artifacts, is shown in Figs. 6–15. The experimental course is described below.

3.1. Stage S0: Selection of the first 3D modeling technique and mode of interaction

The designer begins the creation process by generating a pool of "sketchy" design frameworks that conceptually represent the first outline of the designed interior partition. At this stage, these are meant to be fuzzy and abstract. To achieve this, the animation technique is selected. The designer chooses it because it offers the possibility of generating abstract design representations using, e.g., particle clouds, without the need to express the design intentions using specific surfaces. According to the designer, the animation environment also fosters the use of computational simulations as means to promote unconventional thinking about form design. Instead of direct modeling of surfaces, one can set up systems that generate design frameworks for building future surfaces. These are not shaped by hand but using simulations employing virtual deforming forces. Importantly for the designer, even though the computer performs the simulations, one can decide on the input parameters of the entire system. Employing animation also allows for the designer to enter a favorable balanced human-machine collaboration mode. In this mode, use of the computer enables easy divergence of the solution space, achieved by the rapid automated generation of multiple design alternatives displayed in consecutive animation frames that can be viewed directly in the 3D GUI. The designer can visually assess these alternatives as they are generated and modify the animation parameters on the fly, which the designer sees as promoting spontaneous design explorations.

3.2. Stage S1: Balanced human-machine collaboration in the animation environment

Considering the above, the designer employs a particle-force animation system for the first stage of concept development. The animation scene is set up by creating a particle cloud with four rotating forces, randomly distributed within the limits of the cloud. The conceptual and abstract idea behind this setup is to accentuate certain areas of the partition by disturbing their outline more dramatically than other parts of the wall. In a sequence of ten animation frames, the digital particle simulation performed by the computer generates the effect of a gradual dispersion of the particles under the forces' influence, with stronger disturbances visible at force locations.

Upon visual examination of the animation-generated particle arrangements, the designer notices that the compositions are only slightly differentiated. Therefore, the force parameters are modified, including alterations of the speed and range of particle capture. The designer then reruns the simulation several times, observing the ongoing effects, iterating through parameter settings, and searching through the solutions until a desired differentiation effect is reached. The final design representations at this design stage encompass ten different 3D compositions of particles, differentiating in the proximity of the forces, manifested by circular particle distributions. Within each animation frame representing the design idea, the circular particle whirlpools gradually change their sizes and shapes, cumulating and spreading in space.

3.3. Transition T1

At this point, the designer shifts towards the next design development phase, in which ultimately one of the particle compositions – the most diversified one – is to be used as a framework for the construction of the outline of the architectural partition (Fig. 6). The aim at this point is to turn the fuzzy particle arrangement into an actual 3D surface. This shift in the design development also triggers a shift in the modeling method and interaction mode.

The designer now explores the possibilities of using the particles as surface construction frameworks in two different ways: automated and intuitive. A decision is made to shift from animation-based modeling to two other techniques: algorithmic modeling and freeform modeling. The designer comments that this decision is motivated by the previous experience with the 3D modeling possibilities offered by these techniques and the desire to see what kind of effects they will lead to.

The design process therefore diverges into two scenarios, marked by two new techniques and two interaction modes. In

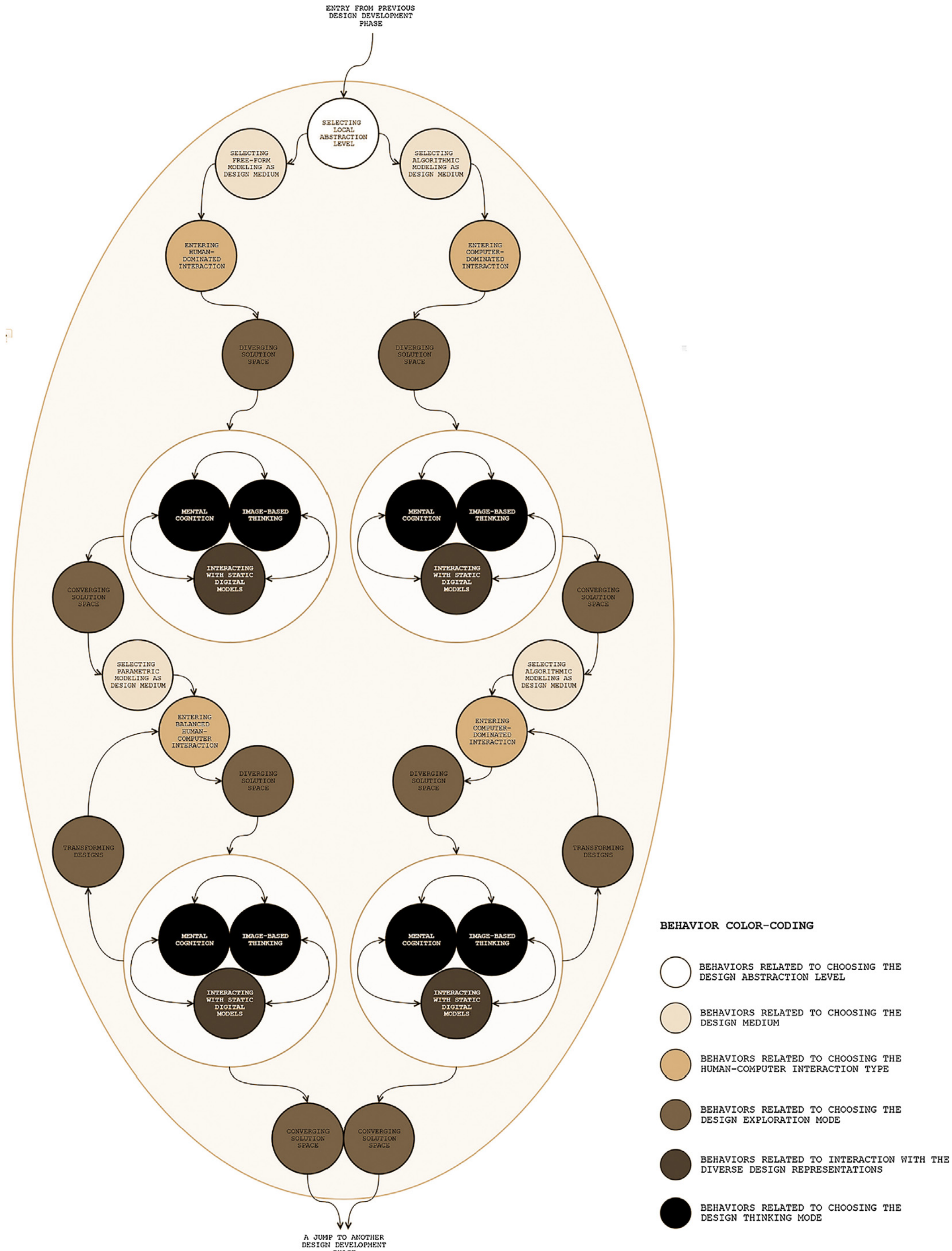

Fig. 5. Sample of creative designer behaviors occurring in a fragment of the design process supported by the hybrid digital toolset.

the first scenario (a), the designer lets the computer steer the process entirely. A surface is automatically generated by the computer from the particles using a dedicated algorithmic plugin. In the second scenario (b), the intention is to create the surface by manual 3D modeling and the designer selects freeform modeling for this task. The design stages and 3D modeling method transitions for these scenarios are presented below.

3.4. Scenario (a)

3.4.1. Stage S2a: Machine-dominated mode using an algorithmic tool

In this scenario, embracing an automated workflow, the designer works with faceted surface representations – meshes. An off-the-shelf algorithmic plugin employing the marching cubes algorithm is applied. The meshing algorithm automatically creates ten meshes from the ten animation-derived point clouds. At this point, the designer does not steer the way the algorithm is executed, as the resultant meshes are the result of a purely automated process without access to its detailed computational controls. The meshes are visually examined by the designer and one is selected for further design development (Fig. 7).

3.4.2. Transition T2a

Upon the examination of the chosen automatically generated mesh, the designer notices imperfections in its triangulation, and consequently wishes to fine-tune the meshing pattern. However,

Fig. 6. Particle cloud object derived using the animation technique.

for this fine-tuning, the designer wants to access the surface directly, and regain full control of how it will be modified. Therefore, a decision is made to shift to an opposite work mode, an intuitive one instead of an automated one. The shift in the interaction mode also means a shift in the 3D modeling method from algorithmic to freeform.

3.4.3. Stage S3a: Human-dominated mode using freeform modeling

Using the freeform 3D modeling technique, the designer can perform the desired manual modifications of the mesh. The mesh borders are refined by manually cropping out the middle portion. Some of the mesh vertices are moved in space to locally correct the irregular meshing patterns. Some of the openings in the mesh are patched to generate a continuous surface effect. To open a space for further compositional exploration of the mesh in subsequent stages, the designer intuitively dissects the mesh, which results in the extraction of three islands in the middle of the main mesh. The designer comments that this will enable selectively applying different types of ornamentation to the extracted mesh areas later. The designer also appreciated the fact that it was possible to perform the above surface modifications intuitively by hand.

3.4.4. Transition T3a

In its current state, the mesh has a very rough tessellation pattern, which the designer dislikes. Therefore, the designer wants to employ an automated process of its recomputation to fix this effect. A decision is made to algorithmically fine-tune the tessellation pattern and smooth out the mesh. Previous knowledge and experience with algorithmic modeling allow for the designer to directly select a tool that is most suitable for this purpose: a dedicated algorithmic add-in for mesh subdivision.

3.4.5. Stage S4a/S5a: Balanced human-machine collaboration using an algorithmic tool

The tool used in the first phase (4a) of this design stage reappears in the form of an off-the-shelf plug-in. This plugin allows for a high level of control over the computational process and gives access to its source code and process parameters. Based on previous experience with the tool, the designer decides that altering the source code will not be necessary to reach the exploration goals at this point, as tampering with the code "will cause an unnecessary disturbance in the design thinking flow" of the process. The designer is convinced that the changes of the process parameters will suffice for explorative purposes. The available options are: the type of the subdivision algorithm (Catmull-Clark, Loop, Sierpinsky triangles and a few custom ones), the subdivision level (from 1 onwards) and the treatment method for the naked edges of the mesh (fixed, corner-fixed and smooth). The designer playfully experiments with the different combinations of the above options, observing the esthetic results and assessing their esthetic quality. For the final options, Loop's subdivision algorithm is chosen with

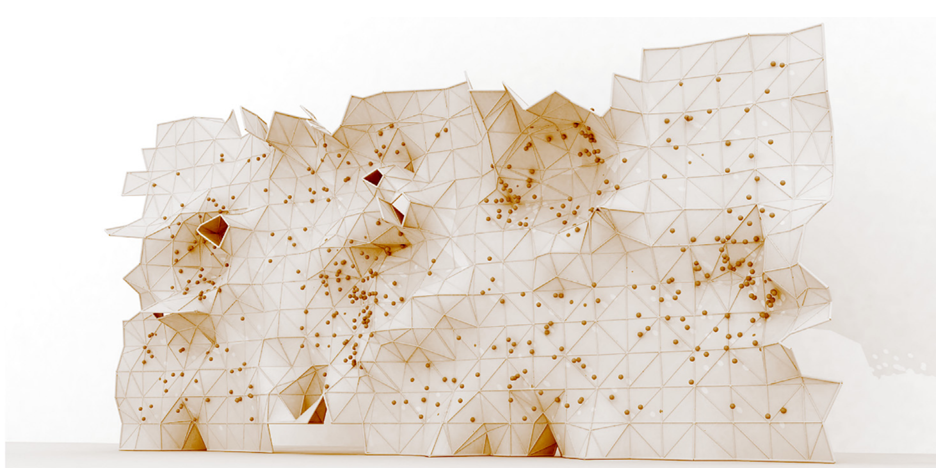

Fig. 7. Mesh surface generated from the particle cloud using the algorithmic technique.

the subdivision level set to 1 and a fixed naked edge treatment. The rough mesh is now computationally refined by densifying its triangulation pattern. The new mesh exhibits a smoother appearance that is highly valued by the designer (Fig. 8).

The next stage of development for this scenario (5a) comprises ornamentation of the generated surface. The designer's intention at this point is to obtain two types of decorations: one that is permeable to vision and light and one that is opaque. To achieve these decorative goals, the designer continues working in the balanced human-machine interaction mode and using the algorithmic modeling technique.

This decision is motivated by the designer's experience with algorithmic mesh modeling and the belief of the designer that this method offers interesting possibilities for further detailed design of mesh-based geometries. The intention is to apply various meshing algorithms that the designer is already familiar with to produce surface decorations. The dedicated algorithmic add-ins feature a desired balanced interaction mode that allows for the designer to access some of the process parameters. Using these add-ins, the designer augments the algorithmic alterations onto the meshed surfaces, iteratively altering some of the available parameters for each algorithm applied. The opaque ornament is created by using an algorithm that extrudes the center points of the mesh faces. The permeable decoration is generated by an algorithm that offsets the boundaries of the mesh faces, thickening them and adding holes. Both algorithmic tools give access to the process parameters, allowing for the designer to experiment with different settings for extrusions, thickening and perforations. As a result of these explorations, three different design artifacts were generated: one that is opaque, one that is permeable, and one that contains a mixture of decorations – nonpermeable for the main mesh body, and permeable for the smaller parts (Fig. 9).

3.4.6. Transition T5a

Based on the quality of the esthetic results, the designer assesses that the process of working with digital models has reached its limits and is complete and wishes to enter a materialization phase. Based on previous experience with a variety of rapid prototyping methods, the designer selects 3D printing as the most suitable technique for producing the physical embodiments of the geometrically complex digital models. The choice of 3D printing is also motivated by the previous experience of the designer with configuring the material deposition processes using the FDM 3D printing technique. This technique was selected due to the high level of accessibility of the process parameters.

3.4.7. Stage S6a: Balanced human-machine collaboration in the 3D printing environment

The designer engages with the rapid prototyping process parameters using dedicated FDM 3D printer software that gives access to a JSON configuration file containing all editable settings used to compile the final machine code. The parameters modified by the designer to explore the esthetic effects of the 3D printing process include: the layer heights and widths and their ratios and extreme values; the number and spacing of the outer shells; the infill thickness, pattern and density; the material deposition speeds at various moments of the building process; the nozzle temperature; and the nozzle travel speed. The machine generates a number of smaller 3D-printed physical mockups, which help the designer establish the final set of the parameters applied for the final two prints (Fig. 10).

3.4.8. Transition T6a

With two final physical 3D-printed plastic models, the designer now engages the senses of sight and touch to investigate their visual and tactile properties. Illumination of the models, from both the front and back, is used to examine how the plastic accentuates the forms' complexity and detailed features. Touch is also employed to examine the models' textures. These actions result in the decision to change the 3D printing method. The designer assesses the esthetics of the plastic models as interesting but "sketchy". A conclusion is made that the models are too rough. Higher accuracy of the models and a "finished look" are desired. Therefore, a decision is made to shift from FDM to CJP 3D printing. From previous experience, the designer is aware that the latter technique offers little possibility to experiment with the print settings, but decides that the automated character of CJP printing will ensure a high quality print, which is now the priority.

3.4.9. Stage S7a: Machine-dominated mode of 3D printing

The designer imports the digital models into a dedicated CJP 3D printer software environment that generates machine code. Despite the highly automated character of the process, the designer can determine the orientation of the model (standing or lying down) on the printer bed while building. The designer's previous experience with the technique indicates that model positioning affects the esthetics of its surface finish – even though very thin, the boundaries of layers of the printed material are visible on the surface. The designer decides to lay the models flat to obtain a particular orientation of the layer strata on the model surface, i.e., one resembling the contour lines of a topographic surface repre-

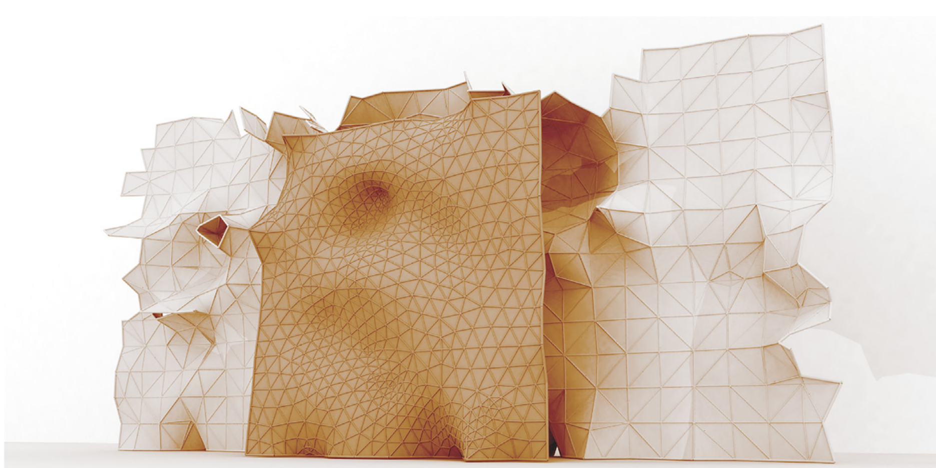

Fig. 8. Mesh surface cropped using the freeform modeling technique and refined using the algorithmic technique.

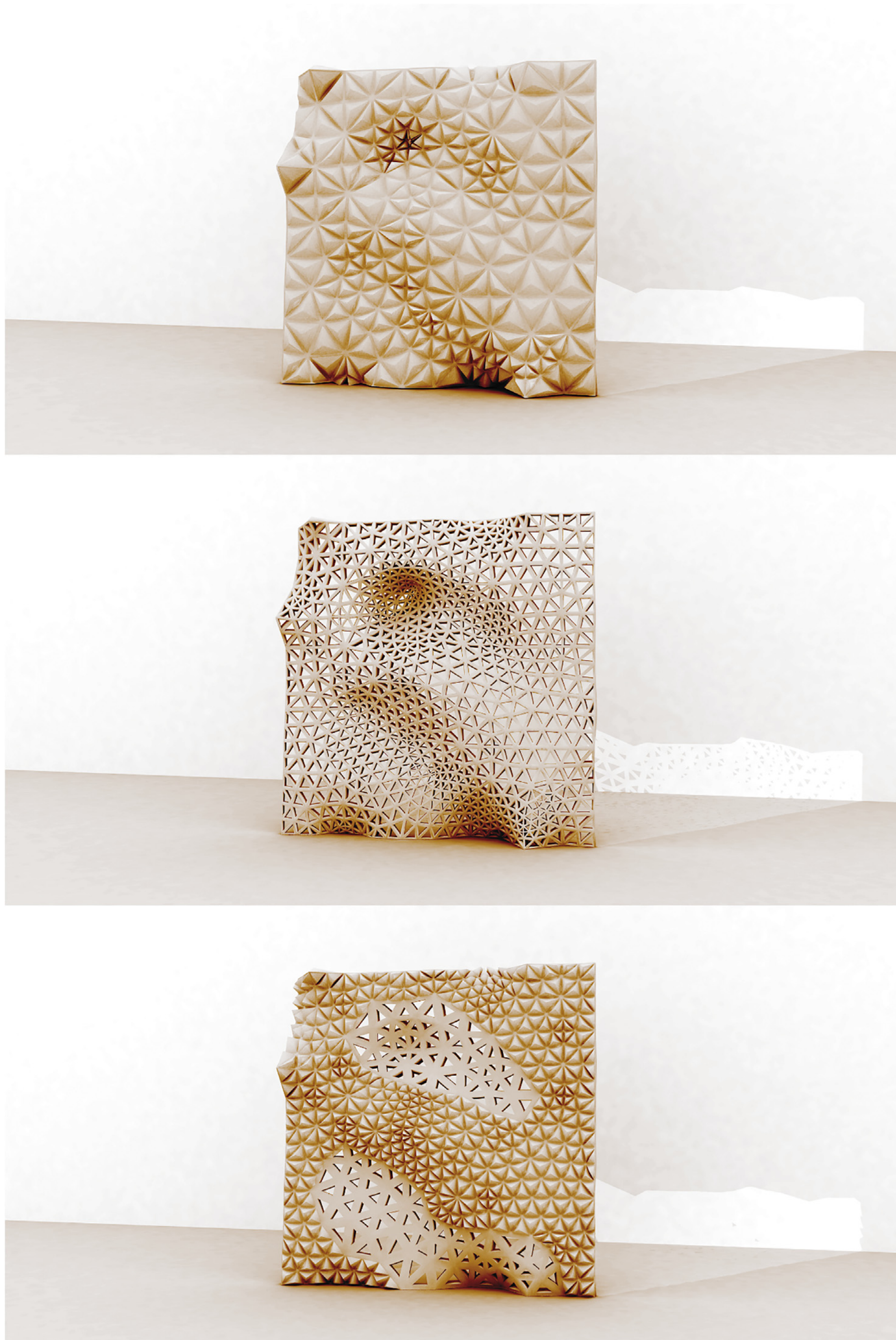

Fig. 9. Opaque (top), perforated (middle) and variegated (bottom) mesh surface ornamentation generated using the algorithmic technique.

sentation. The models are then fabricated in gypsum (Fig. 11) and examined visually and tangibly. The designer is satisfied with the layered effect on the gypsum surface and appreciates the ability of the strata to refract light and create a unique light and shadow interplay on the objects' surfaces. This guides the decision to end this creation scenario.

3.5. Scenario (b)

3.5.1. Stage S2b: Human-dominated mode using freeform modeling

In the second scenario, embracing the intuitive freeform modeling workflow, the designer intends to work with smooth NURBS (nonuniform rational B-spline) surfaces. The process begins with the intuitive selection of some of the particles from the particle cloud generated in Stage 1 as guiding points to manually construct eight freeform curves. These curves are then used as a framework for the modeling of a freeform surface (Fig. 12).

Once the surface is created, the designer modifies it manually and intuitively by slicing it vertically. As a result, two surfaces arise. Based on esthetic judgement and intuition, the designer chooses one for further development (Fig. 13). Similar to the mesh case above, this smaller selected surface is further sliced manually into longitudinal patches, which allow for the designer to augment specific areas with varying ornaments later.

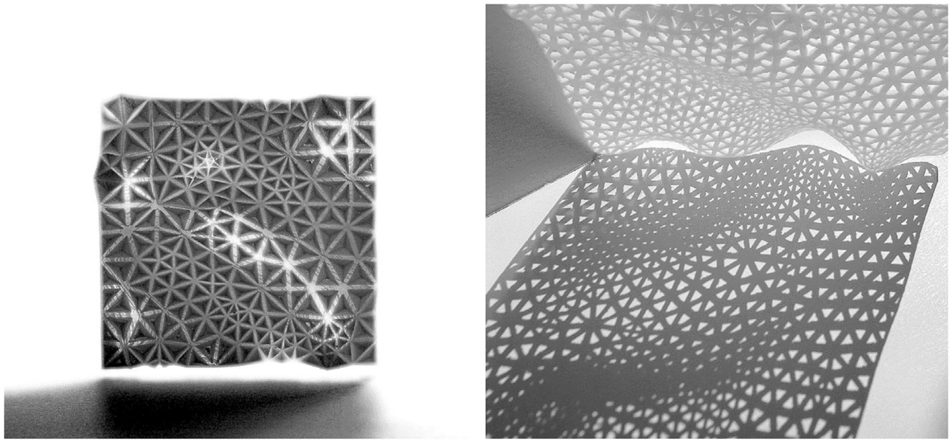

Fig. 10. Two illuminated plastic models produced using the 3D printer.

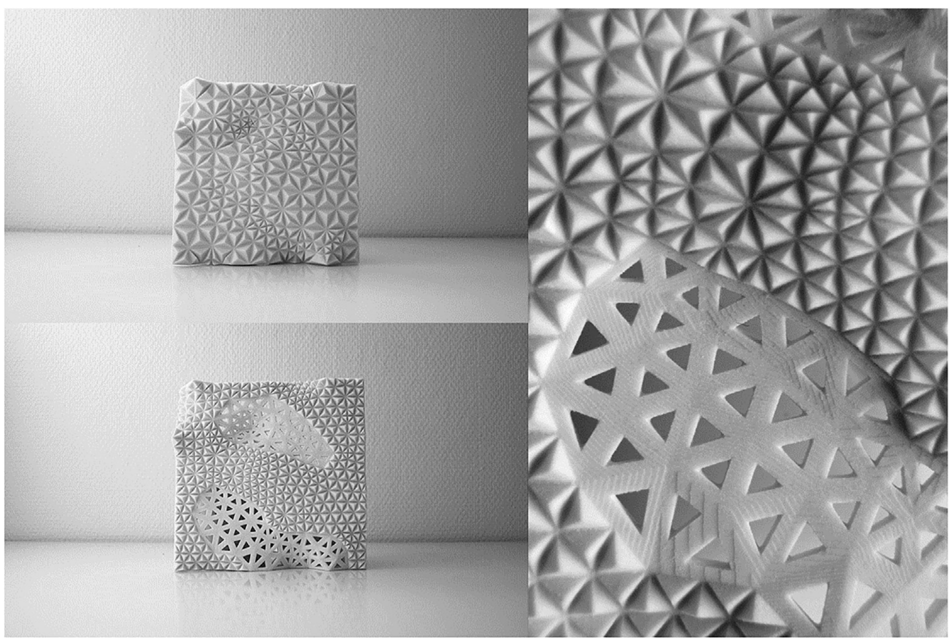

Fig. 11. Gypsum models from Scenario (a) produced using the 3D printer, showing the visible surface layering from the 3D printing process.

3.5.2. Transition T2b

At this point, the designer concludes that the creation limits for manual modeling of the surface have been reached. They desire to acquire a higher level of control over the surface shape than the freeform modeling technique offers. From previous experience, the designer knows that the parametric modeling technique allows for precise mathematical and parametric control of the surface geometry in a balanced human-machine collaboration environment, and this technique is selected as the next tool.

3.5.3. Stage S3b: Balanced human-machine collaboration mode using parametric modeling

To prepare for the parametric modeling stage, the designer creates two elements using the freeform modeling technique: a solid block with tampered edges and a perforated piece. The idea is to inscribe these elements parametrically onto the smooth surface so that they follow its curvature. The designer now shifts to the parametric modeling technique. The surfaces to be augmented with ornaments are fed into a visual scripting-enabled parametric environment and parameterized. Then, parametric controls for surface division are defined to divide the surfaces into compartments that will become the placeholders for the decorative elements. The compartmentalization is steered by the numeric values set by the designer, with the goal of changing the compartment distributions on each surface patch. By playfully manipulating those values, the designer explores variations of the decoration layout. Having chosen the final composition, the designer then creates parametric instructions that inscribe the solid and perforated modeled elements into each compartment. Three designs were generated from this process, as with the mesh case: one that is opaque, one that is permeable, and one that contains both opaque and permeable decorative stripes (Fig. 14).

3.5.4. Transition T3b

At this point, the designer assesses that the esthetic quality of the results is satisfying and that the limits of the creation process in the digital environment have been reached. The designer now wishes to enter a materialization phase. Using the knowledge from Scenario (a) and driven by the intention to produce models with a high-quality surface finish, the designer decides to employ the machine-dominated process of automated CJP 3D printing.

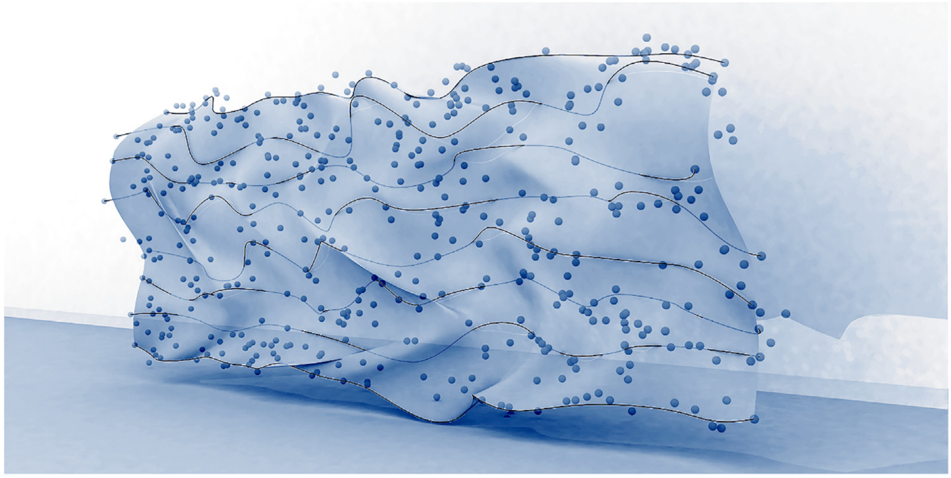

Fig. 12. Curves and smooth surface constructed using the freeform modeling technique, derived from the animation-generated particle cloud.

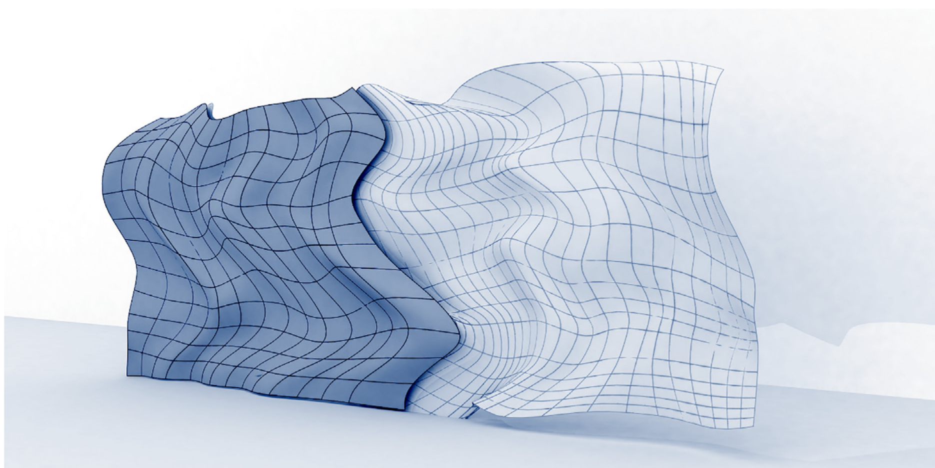

Fig. 13. Smooth surface sliced and extracted manually using the freeform modeling technique.

3.5.5. Stage S4b: Machine-dominated mode of 3D printing

The designer again imports the digital models into a dedicated 3D printer software and orients them lying down on the printer bed. Three models are generated as a result of the printing process (Fig. 15). The designer is satisfied with the appearance of the random strata that appear on the models' surfaces as a byproduct of the 3D printing process. The strata produce striking textural effects and contribute to the high tactility of the models, which is appreciated by the designer. With the desired esthetic result, the design process for Scenario (b) is terminated.

4. Discussion of the results

To provide a reference context for the discussion of the hybrid toolset experiment results, we consider how the design process in that experiment differs from the analogical process typical for mainstream digital architectural practice. Before this comparative analysis, we briefly introduce a typical process and its course.

4.1. Typical digital design process in mainstream practice

The early-stage development process in the mainstream digital architectural practice typically involves a limited digital tool repertoire. It commonly employs one or two different modeling techniques. A popular approach involves freeform modeling and parametric modeling to combine intuitive manual creation with the possibility of mathematical control of the generated geometries. To outline how an architectural design process employing such a typical digital toolset may proceed, we introduce a design experiment with prerequisites identical to those of the hybrid toolset experiment in Section 3. The designer's task is to develop an early concept for a decorative interior space partition using a toolset consisting of freeform modeling and parametric modeling. The stages and transitions accompanying the design concept development for such a case are described below.

4.1.1. Stage S0: Selection of the first 3D modeling technique and interaction mode (human-dominated freeform modeling)

The designer wants to begin by working intuitively. The goal is to create a surface that represents the overall shape of the partition. For this purpose, freeform modeling and its human-dominated interaction mode is chosen. The designer first draws a simple, rectangular planar surface. Then, the control points of that surface are manipulated along planes perpendicular to the main surface to deform it into a double-curved surface. The designer continues to move the control points until a visually satisfying curved surface outline emerges (Fig. 16).

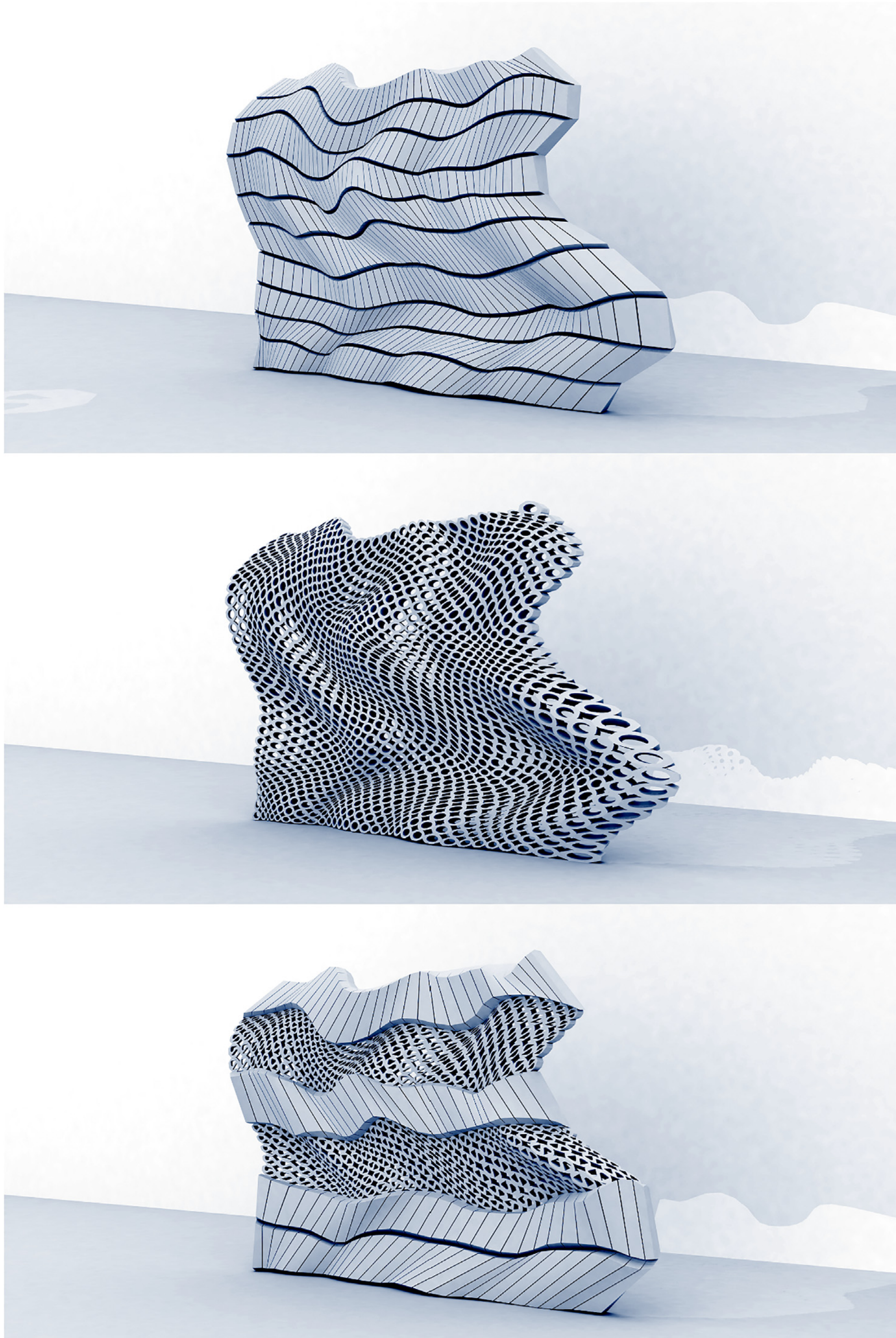

Fig. 14. Opaque (top), perforated (middle) and variegated (bottom) smooth surface ornamentation generated using the parametric modeling technique.

4.1.2. Transition T1

In the next stage of creation, the designer augments the created surface with decorations. The designer knows from previous experience with freeform modeling that this technique is not well-suited for working with augmented surface decorations. Therefore, a decision is made to switch the technique to parametric modeling. According to the designer, this technique efficiently supports the process of generating the decorations of the surface, allowing for precise mathematical control of the decoration geometry and more intuitive manipulation of its layout.

4.1.3. Stage S1: Balanced human-machine collaboration in the parametric modeling environment

In the parametric environment, the designer wants to create surface decorations in the form of hexagonal modules with circular openings. The process is started by mathematically defining a hexagonal grid with external dimensions matching those of the manually modeled surface. A circle is inscribed in the center point of each grid cell. To avoid uniformity in the openings, a decision is made to modulate the radii of the circular openings by scaling them proportionally based on the distance of each circle from a

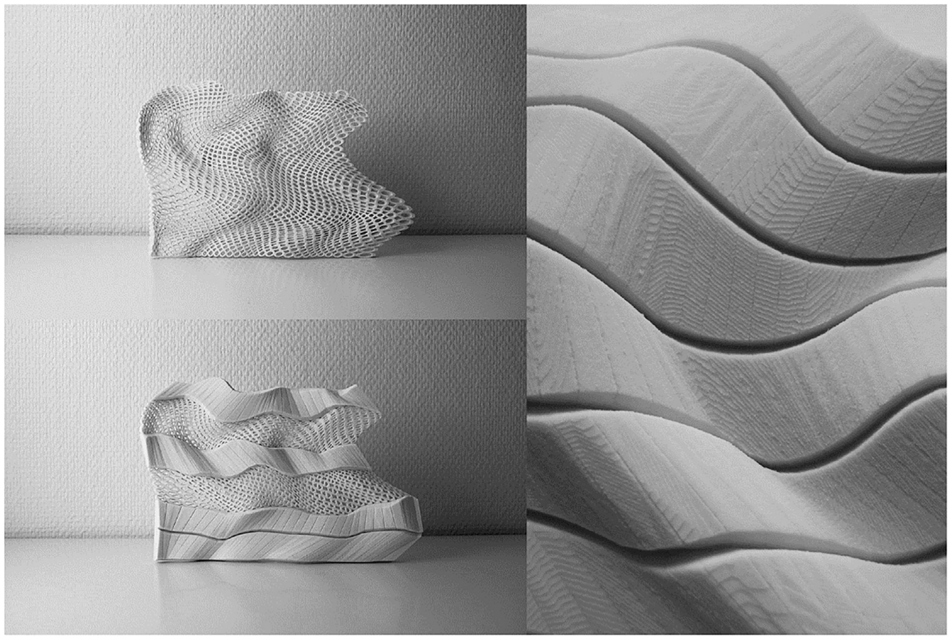

Fig. 15. Gypsum models from Scenario (b) produced using the 3D printer, with visible surface layering from the 3D printing process.

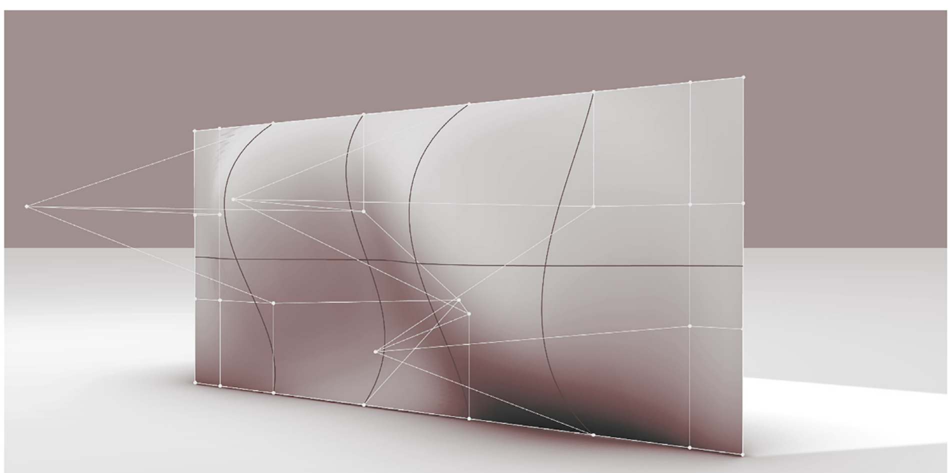

Fig. 16. Double-curved surface shaped manually through control point manipulation in the freeform modeling environment.

point positioned in space (Fig. 17). The point can be moved, enabling intuitive exploration of the circle radii distributions. The designer moves the point in space, with the circle radii changing accordingly, based on the distance from the point. Relatively quickly after moving the point into three different positions, the position generating the most visually interesting opening distribution is identified and selected as the final design option. The hexagons and the opening composition are then projected onto the surface and extruded to form 3D elements (Fig. 18). The design process is finished.

4.2. Simple versus hybrid: A comparison of the toolsets

Following this overview of the typical digital architectural design process that features a limited number of digital tools, we now compare it with the hybrid toolset case. We examine three aspects of interest in this research inquiry: interactions between the designer and the digital media, design thinking characteristics, and the nature of working with design representations.

4.2.1. Interactions with digital tools

As noted in Section 2.1.1., to support creative early design, design media should create favorable conditions for varied interactions between the designer and the computer: human-dominated, machine-dominated and a balanced human-machine cooperation.

In the simple toolset case, two modes of designer interactions with the tools took place: human-dominated and balanced human-machine interactions. The transition between them was straightforward, with the designer switching the modes only once to reach the desired creation goals. One could imagine an extension of this process with the techniques and interaction modes switched more than once during concept development. However, if there are only two modeling techniques and two modes to choose from, it appears that few switches are capable of adding significant value to the explorations. Therefore, it is probable that the exploration process using a limited number of techniques will be rather short. If the designer desires more extended and longer explorations in the early conception stage, the limited choice of modeling techniques and interactions in this simple toolset setup

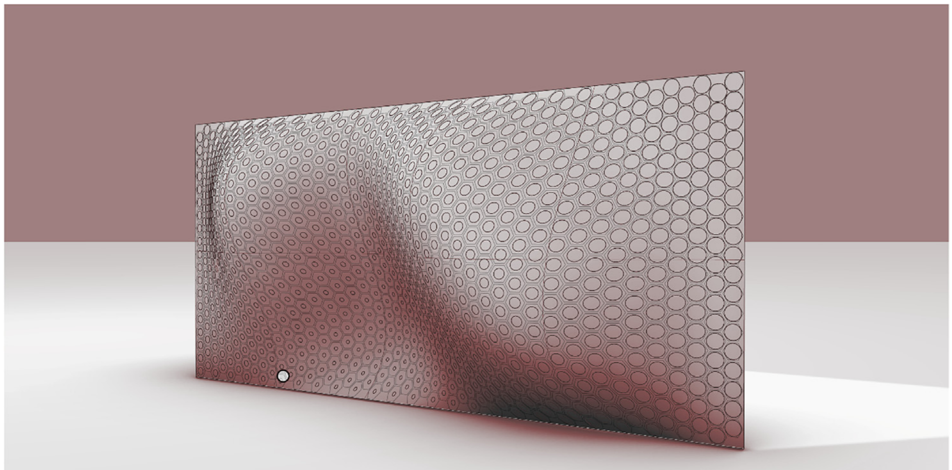

Fig. 17. Final opening distribution created using the parametric modeling technique; the white dot indicates the location of the point that steers the opening sizes.

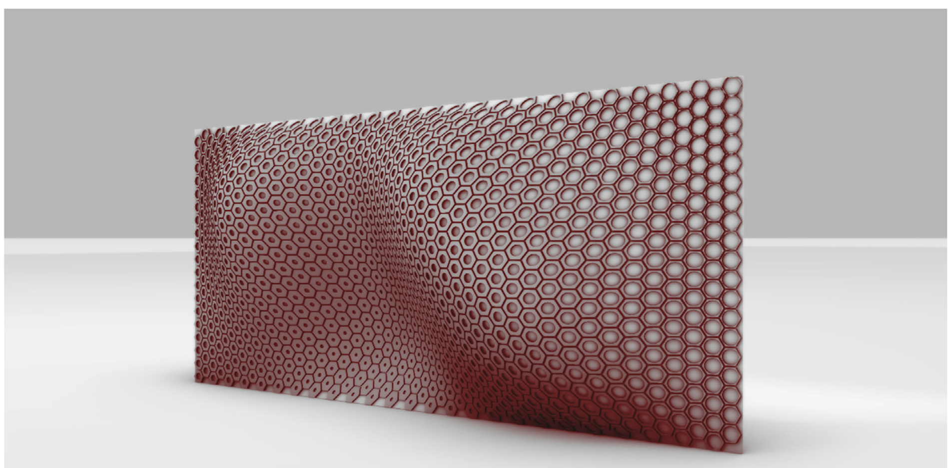

Fig. 18. Final partition design generated using the simplified version of the digital toolset.

may lead to dullness of the design workflows and pose a risk of hindering the designer's creativity.

In the hybrid toolset case, all three modes of interaction were entered. Highly intuitive human behaviors were backed up by fully automated computational procedures. Their balanced mixtures were also featured. Moreover, in the hybrid toolset, the same mode could be employed in different modeling techniques, increasing the variety of interactions. For example, animation-based modeling and parametric modeling both use the balanced interaction mode. However, the logic of modeling is very different for each of these techniques, causing the interactions to manifest themselves differently in practice. In the case of animation, there are interactions with the animated objects such as forces and with the numerical simulation parameters such as force magnitudes. In the parametric environment, most of the focus is placed on manipulation of the parameters and the mathematical or geometrical relationships between objects. Therefore, the design process using the hybrid toolset featured a highly varied interaction environment, which positively affected the creation workflows. The designer could alternate between very intuitive operations involving form finding and manual fine-tuning of the design and the computational actions of the computer to support design tasks that are difficult to carry out manually. This indicates the versatility of the hybrid toolset environment. One could imagine that each new design process could feature different configurations of interactions with the computer and hence be carried out differently even by the same designer, yielding varying results each time.

The decision-making process to switch the interaction mode had similar grounds for both the simple and the hybrid toolset cases. Each design step was informed by the results of the previous step and by the design intentions for the next step. That is, the visual examination and assessment of the esthetic qualities of design representations produced in one design stage triggered and affected the upcoming decisions to continue with the current tool or to switch to another one. For the hybrid toolset case, this decision-making process was more expanded and complex than for the simple toolset due to the larger number of techniques and interaction modes to choose from. It featured a long chain of decisions on transfers between the interaction modes, dictated by ongoing design intentions and the creation needs for the immediate and subsequent design steps, such as the intention to split the surface to be able to augment it with decorations in the later stages of design development.

One common observation that can be derived from both cases is that the decision-making process related to the selection of the modeling technique and the human-machine interaction mode was heavily based on the previous experience of the designer with each modeling technique. This is especially relevant for the successful application of the hybrid toolset. The hybrid toolset experiment emphasizes that the decisions to switch techniques and interaction modes must be rooted in the prior experience of the designer regarding the possibilities and limitations of each technique and its accompanying interaction mode. The remarks of the designer on the capabilities of, e.g., animation (that it allows for quick divergence of the design space), or the limitations of scripting in the algorithmic environment (that it hinders the design thinking flow) clearly indicate that the designer consciously applied techniques and interaction modes to benefit each design step. Thus, the powers of computation, human intuition, and the combination of the two were all employed by the designer in a way that seems optimal, i.e., fitted to the creation needs that emerged as the design process proceeded. The shifts between techniques and interaction modes were done with dexterity and precision, and the character of the entire design workflow remained highly spontaneous and free. This spontaneity and freedom seemed somewhat limited in the simple toolset case. The design workflow therein was largely constrained due to the limitations of the techniques and the fact that there were only two interaction modes to alternate between.

4.2.2. Featured design thinking processes

In Section 2.1.2., we presented the idea of multiple cycles of divergence, transformation and convergence as factors safeguarding meaningful creative design. We also described studies proposing that digital design support tools should enable work on all abstraction levels: global, local and detailed.

In the simple toolset case, the design thinking process relied heavily on the transformations of a single design concept. In the freeform modeling phase, this comprised a linear sequence of manipulations of control points of one surface to arrive at a desired shape. Because all transformations were applied to the same surface in succession, the designer did not diverge the solution space in the classic sense. This would be the case if the surface was copied multiple times, each of the copies were transformed differently, and the final output was chosen by visually comparing the differently transformed models side by side. In the parametric modeling phase, the design development was also based on a linear sequence of transformations applied to the same 3D model. It comprised successive moves of the attractor point in space to generate different resizing options for a decorative element of the same type. The design process did not feature classic divergence and convergence of the design space. This is illustrated by the morphologically similar character of the sequentially generated design 'options'. Although one could also imagine a more diverse design versioning, for example, by introducing more than one attractor point or several attractor curves, it seems that this particular toolset combination – freeform modeling and parametric modeling – may favor design transformations over classic divergence and convergence and, if those occur, they will be somewhat limited in their scope and resulting diversity.

The design process carried out using the hybrid toolset featured all three cognitive activities – divergence, transformation and convergence, and none of these appeared to be favored over the others. In terms of divergence, the solution spaces were generated and diversified more than once – for example, when involving animation and parametric modeling. Further, during animation, algorithmic modeling using the mesh from points algorithm, and parametric modeling, the designer intentionally generated different design representations in parallel, assessing them visually side by side. Some of these comparisons done at the beginning of the creation process could have inspired the major divergence of the design concept and its creation processes into two radically different paths, one based on mesh geometry and the other based on NURBS geometry.

Multiple design transformations were also supported by the hybrid tooling environment. For instance, the designer modified the properties of the animation forces and the parametric values defining the NURBS surface divisions. This altered the respective solution spaces, allowing for the designer to explore a broader range of design alternatives. Finally, the hybrid environment allowed for the designer to apply convergent design thinking while employing the freeform modeling and algorithmic techniques. At those times, the focus was on selecting single design solutions to achieve a more detailed design. Notably, divergence, transformation and convergence occurred several times as part of iterative design cycles. This richness and often looped character of the design workflow was not present in the simple toolset case, which suggests an advantage of the hybrid toolset environment over its simplified version in terms of design thinking process diversity.

In addition, the hybrid tooling environment's diversity may have stimulated the designer's imagination and cognition, steering it towards unplanned paths that may not have been taken if the hybrid toolset was not used. One example is the early divergence of the design concept into two separate scenarios: one with the tiled mesh and the other with a smooth NURBS surface. This occurred because the designer was aware that the engaged design techniques allowed for alternative paths, offering an opportunity for varying the esthetic development of each design option. Although a number of design paths could also be taken in the case of the simple toolset, it seems that the diversity of the hybrid toolset's 3D modeling media creates a more stimulating environment for these alternative paths to occur at the beginning of the design process and in its intermediate stages.

Regarding the exploration of design abstraction levels, the simple digital toolset case demonstrated that the particular combination of techniques featured therein quickly moved the explorations from the local level to the detailed conceptual level. Most of the design activity and intellectual effort was concentrated on generating the surface decorations, demarcating the detailed level of conceptualization. The limited capacities for design conceptualization in freeform modeling eliminated the possibility of working on a high, global level of design abstraction, necessitating initiation of the work on a quite concrete local level featuring surface shape development. The limited capabilities and precision of freeform modeling caused the designer to quickly switch to parametric modeling. With this technique, the conceptual effort was heavily based on mathematical thinking, i.e., conceiving the numerical and mathematical means (in the form of tying the opening radii to the distance from the attractor point) that allows for diminishing the compositional uniformity of the openings in the partition.

In the hybrid toolset case, the diverse capabilities of the digital techniques available to the designer created a rich environment for developing the design on all levels of abstraction: global, local and detailed. For example, using animation of a particle system with forces, the designer could work with abstract, ephemeral spatial compositions that do not illustrate the design itself, but rather a variety of spatial frameworks that could be used as a base for further developments. It allowed for producing fuzzy object representations – a beneficial quality at the initial stage of concept development. The freeform modeling and algorithmic modeling techniques allowed for the designer work on the local abstraction level, adding more information to the conceptual constructs derived at the high level of abstraction. Thus, the freeform modeling enabled the creation of surfaces based on fuzzy particle compositions and algorithmic modeling allowed for producing more concrete surface representations by employing computational routines. Finally, parametric modeling lifted the design to the detailed abstraction level. The designer began controlling the design very precisely at every fragment of the surface. The discrete parts of the design, including the meshed surface's tessellations, the smooth surface's divisions, and the sizes of the augmented decorative elements, were explored in detail with the aid of algorithms and numerical values that affected their composition and distribution.

4.2.3. Design representation aspects

The studies presented in Section 2.1.3 argue that robust digital design support systems should stimulate the designer to produce miscellaneous design representations and artifacts. A wide variety of designer interactions catalyze the idea generation processes and evoke extensive creative explorations.

In the simple toolset case, the number of produced design representations was moderate, with the freeform phase yielding two consecutive representations (flat surface and its manipulated double-curved version) and the parametric phase featuring two principle representations (a flat initial hexagon grid with identical circular openings and its modulated version with the final projection onto the surface as 3D elements). These representations were digital and static. The representations differed slightly in character, featuring both curve and surface representations and were concrete rather than abstract. Nonetheless, the moderate number and rather uniform character of the representations represented the design concept well enough, i.e., the design development process and its results were clear to understand. Although there were relatively few resulting representations, the designer was able to operate within the visual cognition zone and employ image-based thinking, stimulated by what appeared on the computer screen to explore variations of surface curvatures during freeform modeling and variations of the opening modulations in the parametric modeling phase. However, compared with the hybrid toolset case discussed below, these visual cognition processes and interactions with the representations are rather narrow in scope.

In the hybrid toolset case, the design representations were much more numerous and variegated. Over 30 representations were generated. These were both digital and physical, with varying levels of specificity and detail, ranging from fuzzy outlines of design objects to their concrete physical embodiments. The designer actualized them in forms favored by designers in early-stage creation: 2D drawings, 3D visualizations and physical models. This illustrates that the hybrid toolset supported the designer in the creation of this wide representation range. Moreover, the representations produced using animation and parametric modeling techniques were dynamic. The changes in their 3D appearance could be simulated in a time-based process of geometric transformation. This further stimulated the designer's cognition and imagination.

Working within the hybrid digital domain also allowed for the designer to interact with the created representations. As noted above, the diverse sensory stimuli provided by both static and dynamic images produced within the digital environment and by the physical forms of 3D-printed artifacts triggered intensive processes of design thinking – image-based thinking involving divergence, transformation and convergence, and active exploration of designs at various abstraction levels. An advantage of the interaction with the digital representations was that there was no need to erase the artifacts to explore their alternative configurations, as in traditional paper-based design. For example, by altering the animation settings, the designer could instantly affect the design artifacts viewed on screen. The applied changes appeared instantly, giving quick visual and esthetic feedback on the different element compositions. This feedback was of a three-dimensional and dynamic character, which made it much easier to interact with the different compositions visually by viewing them from multiple standpoints and observing how they change. The physical artifacts, produced using the rapid prototyping techniques allowed for the designer to interact with design representations in a traditional mode. The models were investigated visually and tangibly, and the insights from those examinations guided decisions on the materiality of the final design.

Table 1
A comparison between the simple and hybrid toolsets; the dots indicate the presence of a particular design process feature.

Feature		Simple	Hybrid
Interaction mode	Human-dominated	•	•
	Balanced	•	•
	Machine-dominated		•
Design thinking	Divergence		•
	Transformation	•	•
	Convergence		•
Design abstraction	Global		•
	Local	•	•
	Detailed	•	•
Design representations	Static	•	•
	Dynamic		•
	Digital	•	•
	Physical		•

4.2.4. Result synthesis

Table 1 presents the occurrences of particular digital design process features in the simple and the hybrid digital toolset cases. The comparison of these occurrences indicates that the typical digital design process, featuring a simple toolset, is somewhat deficient compared to its extended hybrid version.

The hybrid toolset supports a broader and more diverse range of human-machine interaction modes and their possible combinations than its simplified version from mainstream practice. This richness of interactions offered by the hybrid toolset seems to directly influence the quality and quantity of the design thinking processes carried out by the designer. In the hybrid toolset case, the high level of interaction diversity seems to increase the diversity and number of cognitive activities, resulting in the occurrence of multiple looped cycles of design space convergence, transformation and divergence. In the typical simple digital toolset case, the interaction scopes and cognitive activities are very limited. Similarly, the diversity of 3D modeling workflows offered by the different design media in the hybrid toolset opens up the design exploration space more significantly than in the simple toolset version. In the hybrid tooling environment, the designer can explore very abstract design representations on the global abstraction level, as well as very detailed and concretized ones. For the simple toolset case, this capacity is largely limited and may even be narrowed to explorations on one particular level of abstraction. A similar conclusion can be drawn for the levels of diversity of design representations for both toolsets. The diversity of design tools in the hybrid toolset results in the diversity of the supported types of design representations. These range from supporting the modeling of static objects, enabling time-based simulations of object deformations or displacements, and the materialization of physical models. This is not the case for the typical simple digital toolset, as the small number of tools cannot support such diversified representations.

5. Conclusions

The objective of this research was to challenge the notion of using a limited number of digital tools for early-stage design exploration of architectural concepts. The goal was to explore the application of a more diverse, extended digital toolset containing many distinct digital techniques for 3D modeling and materialization. We supported our argument by analyzing and comparing how diversification of the digital tool repertoire influences three design process features, human-machine interactions, design thinking and exploration of design representations, in the advocated extended hybrid tooling approach and its typically simplified version from mainstream architectural practice.

The general conclusion is that increasing the number and diversity of the digital tools is promising to enrich the course and results of the architectural design exploration process. The resulting enrichment demonstrates itself through a significant broadening of the design exploration space that leads to the increase in the number of design alternatives developed. Although the design results of a typical digital design process employing a limited number of digital tools are not trivial or overly simple, our study indicates that its extended version, featuring the hybrid toolset, offers a significantly larger number of design options, including the intermediate options created throughout the exploration process and the final ones. In the typical process featuring the simplified toolset, one design option is often explored, with some slight variations of that option, whereas the hybrid process can yield several morphologically different design alternatives. According to design creativity research, this diversity of design alternatives and the general large size of the design solution space generated using the hybrid toolset may result in the emergence of a better design result that bears the features of creativity and innovation (Gero, 1992).

In addition, the use of a more diverse and vast collection of digital tools has some interesting implications for the design cognition processes. Early stage explorations can extend far beyond linear and straightforward design thinking processes. They can include complex, looped cognitive explorations, enriched with distinct mixtures of intuitive and computational routines. In the typical setup featuring a limited number of digital tools, the role of the tools seems rather classic, i.e., primarily facilitating graphical representation of a design concept in the form of 2D or 3D drawings or physical models. When employing a vast repertoire of digital tools, the role of the tools shifts profoundly. The tools become true partners of the designer and creative stimulators of design thinking processes. They trigger spontaneous design workflows that are not anticipated at the beginning of the process, making its course more rich and open-ended, and therefore possibly more appealing for designers from the standpoint of boosting their design creativity. In the extended human-computer partnership facilitated by the hybrid toolset environment, both the designer and the digital design media deeply support and complete each other. The computational system facilitates quick data processing, complexity generation and control and the designer executes creative reasoning, esthetic judgment and inferring processes. For designers, this hybrid work mode could offer an interesting alternative way to capitalize on the great opportunities of application of computers in design.

Declarations of interest

None.

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