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A Design Framework and a Digital Toolset Supporting the Early-Stage Explorations of Responsive Kinetic Building Skin Concepts

Malgorzata A. Zboinska[1], Jan Cudzik[2], Robert Juchnevic[3],
Kacper Radziszewski[4]
[1] Chalmers University of Technology, Department of Architecture [2,3,4] Gdansk University of Technology, Faculty of Architecture
[1] malgorzata.zboinska@wp.pl
[2,3] {jan.cudzik|robertjuch}@gmail.com [4] dali_rad90@yahoo.pl

In this paper we present the first phase of our research on the development of a framework for early-stage responsive kinetic building skin design. The aims of this study were: to formulate a methodological and instrumental basis for the construction of the framework, to conduct an initial pre-assessment of its features, and finally to provide the first example of how the framework could be applied in practice. Importantly, at this point our goal was not yet to indicate the framework's effectiveness, but rather focus on formulating its foundations. A pilot design experiment, aimed at the probing of the framework's characteristics, suggests the emergence of its two noteworthy features. Firstly, it allows to freely but at the same time also systematically explore six design aspects of responsive architecture: form, functionality, performance, kinetic behaviors, system mechanics and responsiveness. Secondly, it helps to explore these six aspects using diverse means: parametric models, digital simulations, computational analyses, physical models and interactive prototypes. These features suggest that the framework could be a valid and useful means of supporting designers in the complex task of creating architectural concepts of responsive kinetic structures.

Keywords: *Responsive kinetic architecture, Hybrid digital toolsets, Parametric design, Dynamic simulation, Performance analysis, Rapid prototyping*

INTRODUCTION

Research premises and purpose

Due to the spatial and functional complexity of responsive kinetic building skins, their design process is often a complex procedure, in which multiple design aspects need to be considered, using a diverse range of advanced digital tools. This inherent complexity of the design process of responsive architecture, especially in the earliest stages, when the design goals tend to remain ill-defined, poses a great challenge for designers, right from the beginning of creation.

Ideally, to guarantee that design efforts are not wasted during such a complicated process, the architect, before proceeding with the creative explorations, should first organize and plan the frame within which the search for the solution will take place. An important factor will be to decide which particular design aspects will be explored at the concept stage, and which design tools will be used to investigate them. Obviously, making those decisions requires taking focus off the actual design explorations for a certain period of time in the conceptual design timeline. Moreover, it is actually quite difficult to make those decisions while the design goals are still not yet precisely clear.

As a remedy to these issues, this study introduces and examines a design framework and a digital toolset, which are meant to serve as a methodological and instrumental base, from which the early-stage explorations of responsive architecture can be launched.

Our proposal in light of the current state-of-the-art

Given that responsive architecture promises to positively affect the sustainability of the built environment, it seems that developing design frameworks which aid its complex design process is a well-grounded goal. The need to develop such frameworks has already been noticed by a number of researchers active within the field. The works by Davis et al. (2011), d'Estree Sterk (2003), Hu & Fox (2005), Jeng (2009), Khoo et al. (2011), Pan & Jeng (2008), and Salim et al. (2011) all introduce various proposals of approaches, methods, workflows supporting the design processes of responsive structures.

Nonetheless, despite the important contributions that these works make to the design methodology of responsive architecture, we can notice that in those studies the primary focus is not on the early design stages, but rather on more advanced ones. In other words, many of the present frameworks support the processes of obtaining finalized designs of responsive structures. What is more, the majority of these already existing frameworks are confined, aiding the design processes of single and usually also purely functional design issues of responsive structures, such as their shading performance (Beaman & Bader, 2010), acoustics (Peters et al., 2011) or affordability (Sharaidin & Salim, 2011).

Consequently, our proposal, by targeting the early stages of the design process of responsive architecture, and by aiming to support the explorations of a wider variety of its design issues within one process, is an attempt to make a fresh contribution to the research results that have been developed so far.

Research aims and method of investigation

The aims of this study were: to formulate a methodological and instrumental basis for the construction of the framework, to conduct an initial pre-assessment of its features, and to provide the first example of how the framework could be applied in practice. Importantly, at this point our goal was not yet to indicate the framework's effectiveness, but rather focus on formulating its foundations. The insights gathered in this research phase set the stage for our upcoming extensive experiments, aimed at the verification of the framework's performance in a much wider variety of design cases.

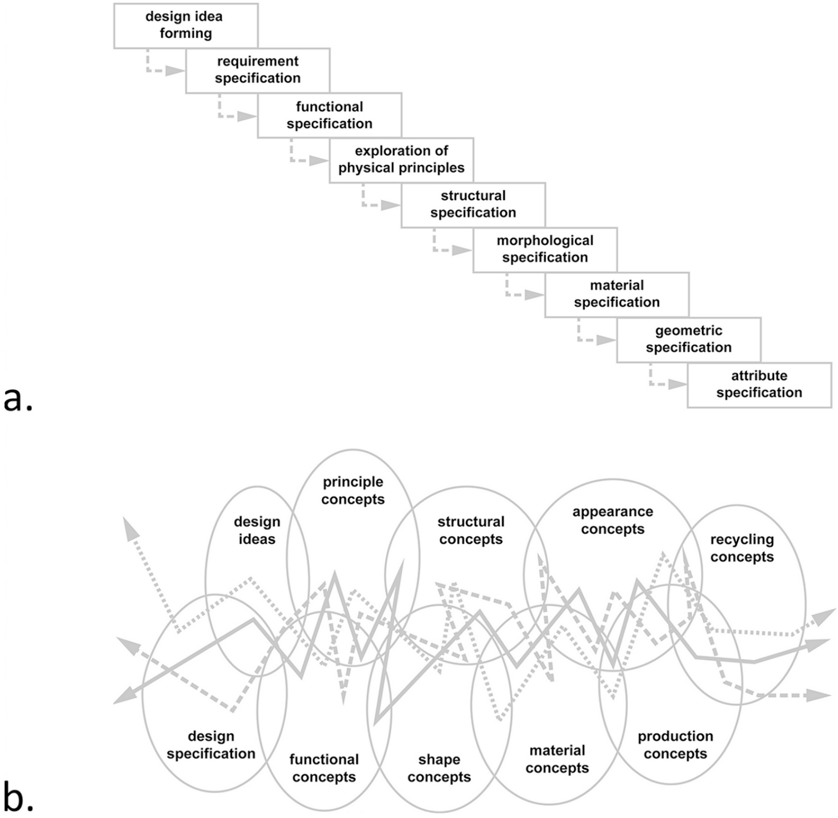
To reach the stated aims, we employed a mixed research methodology, embracing qualitative theoretical analyses of general design process frameworks, followed by practice-based experimentation. Consequently, the framework's development process consisted of a theoretical and an empirical phase. The theoretical phase embraced an analysis of the already existing general frameworks supporting the early-stage design processes. The analysis resulted in finding a framework which seems especially relevant in the context of early-stage design of responsive architecture. Using the found framework as a basis, we then developed one of our own, accompanied by a selection of set of digital tools which we considered suitable for the practical implementation of that new framework.

The empirical research phase embraced a single controlled practice-based experiment, in which the design process of a responsive kinetic building skin was executed using the proposed framework and toolset. A pilot experiment on a single case was considered by us as a necessary element of the investigation, which can help us to identify the framework's potentially-promising features, emerging when it is being applied in the design process. While the goal of the single experiment was not to prove the effectiveness of the framework, it will be used by us as a basis to design the future, much more extensive usability experiments, in which the actual performance of the framework will be assessed. The pilot experiment at this point was accompanied by a protocol-based registration of the design workflows and tasks, applied digital tools, architectural design aspects considered, and finally a catalog of digital and physical artifacts arising from the design process.

A THEORETICAL BASIS FOR CONSTRUCTING THE NEW FRAMEWORK

At the end of the 1970s a structured framework for the early-stage design process was proposed, known in design theory as the waterfall model (Figure 1a). This model postulated that the early-stage design process should be organized into a set of consecutive actions, leading the designer towards the accomplishment of the design goals, which are well-defined

Figure 1
Existing frameworks of the conceptual design process: a. The waterfall model (adopted from Horváth, 2000); b. The pathfinder model (adopted from Horváth, 2000)



before the design process is executed (Roth, 1979). However, the main weakness of such a model was that it required a presupposition of the design activities and their arrangement into a straightforwardly cascading sequence. This stands in a certain opposition to the natural design routines observed in everyday practice (Horváth, 2000). Namely, at the beginning of creation the particular design activities to come are not clearly expressed. In the design process itself, many of them are carried out simultaneously and retrospectively, which frequently makes the exact sequence of their execution impossible to plan in advance.

In the particular case of architectural design, the design problem is characteristically ill-defined initially, and it tends to evolve, together with its solutions, over the course of the entire design process (Dorst & Cross, 2001). Early-stage creation in architecture is therefore a complex enterprise, reaching far beyond an orderly succession of the design acts, as the waterfall model would anticipate. It contains design activities difficult to name and to schedule, often connected by a tangled network of non-obvious relationships (Lawson, 2005).

As an answer to the weaknesses of the waterfall model, the pathfinder model of the conceptual design process was proposed (Horváth, 2000). This model intentionally has a loose structure (Figure 1b). It acknowledges the fluctuating foci of the designer's attention, accepts their overlaps, and it does not specify any particular scenario for their execution. According to the pathfinder model, it is the designer who decides on the type, frequency and order of the design activities, based on the particular needs of the design assignment. The main advantage of such a liberal model is that it permits creative process customization and does not obstruct the thinking and exploration cycles - the occurrences believed to be necessary in successful creative design.

The relevance of the pathfinder model for the conceptual design process of responsive building skins seems high. The design of such structures is necessarily multi-aspectual. The miscellaneous activities must touch upon a variety of design issues, which are often interconnected and which should be explored in an un-prescribed order. Moreover, the foci of interest in responsive architecture design may vary from project to project, depending on the particular functions that the responsive system is meant to play. Hence, flexibility, comprehensiveness and adaptability to the changing design needs are all the necessary qualities required for a universal early-stage design framework for responsive skin design. The pathfinder model promises to offer all of those features within its flexible morphological structure and its unimposing manner of operation.

A DESIGN FRAMEWORK AND A DIGITAL TOOLSET SUPPORTING THE EARLY-STAGE EXPLORATIONS OF RESPONSIVE KINETIC BUILDING SKIN CONCEPTS

Our proposal for the framework supporting the early-stage responsive kinetic building skin design (Figure 2a) is inspired by the pathfinder model. Our framework is built around six main components, connected by a network of feedback links. These six components confine the focus of the designer to the following design aspects of responsive architecture: form, functionality, performance, kinetic behaviors, system mechanics and responsiveness. What enables the exploration of those aspects and their mutual connection throughout the creation process is a cycle of design analysis, synthesis, evaluation, modification and decision-making (Figure 2b), which is executed each time a certain design aspect or a set of aspects is being considered.

To support the use of the framework, a hybrid digital toolbox is also composed, containing a variety of architectural software and hardware. The media from the toolbox are assigned to each of the six design aspects outlined in the framework (Figure 2a). Altogether, the software and hardware gathered in the toolset enable a variety of design activities related to creating concepts of responsive structures: complex geometry creation, variation and editing (Rhinoceros, Grasshopper, Weaverbird, Lunchbox),

Figure 2
The proposed framework for early-stage design of responsive kinetic architecture: a. Framework scheme with software and hardware components; b. A cycle of design analysis, synthesis, evaluation, modification and decision-making, supporting the framework's practical implementation

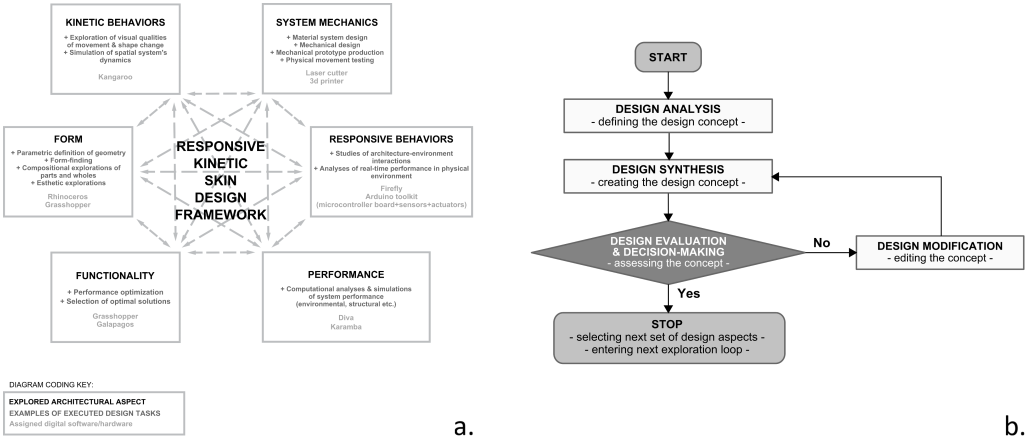
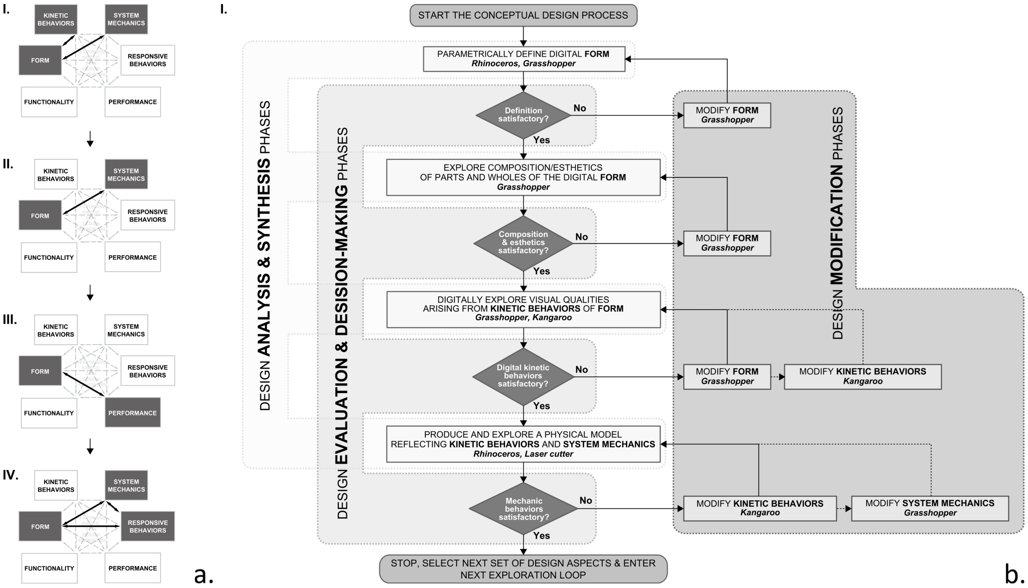


Figure 3
Example scenarios of the practical implementation of the proposed framework, derived from our pilot experiment: a. Various configurations of interactions between selected framework modules; b. Detailed example of the execution of the analysis, synthesis, evaluation, modification and decision-making loop, for design aspect configuration from scheme I of Figure 3a



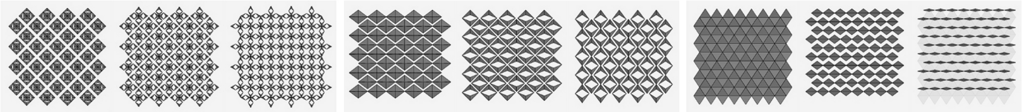


Figure 4
Digital explorations of the esthetic qualities of initial kinetic skin variants, using Grasshopper and the physics simulation engine Kangaroo

performance analysis (Diva, Karamba), dynamic behavior simulation (Kangaroo), performance-driven optimization (Galapagos, Octopus), rapid creation of physical prototypes (3d printing, laser cutting) and interactive prototyping (Firefly and Arduino microcomputer boards, sensors and actuators). Importantly, the entire software part of the hybrid digital toolbox intentionally remains rooted within one environment, i.e. Rhinoceros and its visual programming editor Grasshopper. This minimizes a number of problems related to software interoperability, typically present during the implementation of hybrid digital toolsets based on differing software environments (Zboinska, 2015).

The step-by-step application of the framework and toolset proceeds as follows. Firstly, the designer picks an elective number of design aspects out of the six available ones, based on his/her individual preferences. This can be one aspect or more, in any configuration (Figure 3a). Then, the designer explores those aspects using the digital software and/or hardware tools assigned to the aspects. He/she carries out those explorations by entering a design loop, embracing the phases of design analysis, synthesis, evaluation, modification and decision-making. A detailed example of how such a loop can be executed is shown in Figure 3b, where we present it for one of the phases of our design experiment. The loop is exited once the concept developed at that point of the process is satisfactory. At that point, another set of design aspects is being picked and the development of the concept proceeds further. The newly-chosen aspects are considered using the assigned digital tools, in a looped cycle of design analysis, synthesis, evaluation and modification. After deciding to terminate that second loop, the designer selects yet another set of aspects and then enters a new cycle. The entire process continues and terminates once a satisfactory design concept is found.

THE DESIGN FRAMEWORK IN ACTION: THE RESPONSIVE KINETIC FAÇADE DESIGN EXPERIMENT

The pilot design experiment, aimed at the probing of the features of the developed framework, began in the 3d modeling environment Rhinoceros, using the visual scripting editor Grasshopper, used as a tool to parametrically define the initial form of the responsive kinetic façade, and to explore its compositional and esthetic qualities. Three versions of triangle-based kinetic skin compositions were created and represented in simplified form as zero-thickness surfaces. To investigate the changing visual properties of those skins, the physics simulation engine Kangaroo was employed. It facilitated the explorations of the esthetic aspects arising from the kinetic properties of the skin, such as the changing surface porosity (Figure 4).

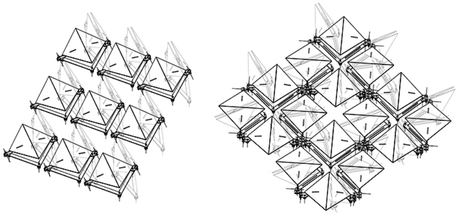


Figure 5
Digital investigations in Rhinoceros of two different kinetic component assemblies, prior to the rapid prototyping of the model using laser cutting

Based on these initial esthetic explorations, the preparation of more detailed versions of the kinetic skin variants was done in Rhinoceros. This was aimed at physical mechanical mockup model production, using the rapid prototyping method of laser cutting. The creation of these materialization-oriented digital 3d models has led to further concept developments. Namely, because at this stage also the prac-

Figure 6
Physical studies of the esthetic, kinetic and mechanical properties of the responsive skin concept using the laser-cut model

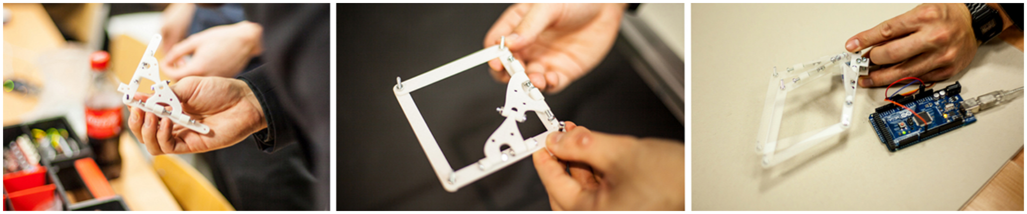


Figure 7
Assembly and testing of the mechanical and dynamic properties of the 3d printed mockup of the kinetic component equipped with an Arduino-controlled servo motor

tical means of activating the structure were considered, and the servo motors were selected for this purpose, the model needed to be adjusted to illustrate the rotary manner of operation typical for the servos. Consequently, the selected edges of the structure were established as rotatable around certain joints, while others were defined as fixed. Before the final model materialization, two digital variants were used as a means to cross-check the composition, esthetic appearance as well as collision risks (Figure 5). Ultimately, the model with the simpler linear arrangement of components was selected for prototyping and assembly.

The existence of the early physical laser-cut model allowed to explore the architectural aspects of the kinetic structure, such as its tectonics, the shadowing and lighting effects arising on its surface during dynamic movement, and the general esthetic appearance of the entire composition of the elements. Moreover, tampering with the model's movable elements has led to further useful discoveries, related to kinetic behaviors and mechanical system dynamics. These indicated that what was feasible in the digital model may not necessarily work in a physical one. For example, the problem of the instability of the kinetic skin covers' mounting and risks of resultant cover collisions were revealed (Figure 6). This information provided valuable clues for the next phase of concept development.

The following design phase embraced the creation of an improved mechanical model of one basic kinetic component. That digital model was prepared with the 3d printing method in mind. This particular rapid prototyping technique was selected because it allowed for the production of a much more detailed prototype, containing custom-designed joints and connectors. The assembly and testing of the movement behavior of the fabricated model revealed its weaknesses in terms of the unstable servo motors' mounting and loose connectivity of the rotatable joints (Figure 7). These issues were later on corrected in the digital model, which resulted in the 3d printed mockup of two kinetic components, in which supplementary stabilizing and mounting elements were added.

In parallel to the explorations of the physical component prototypes, the studies of their esthetic and environmental properties were also performed, in the digital space. The objective was to investigate the consequences of applying the components

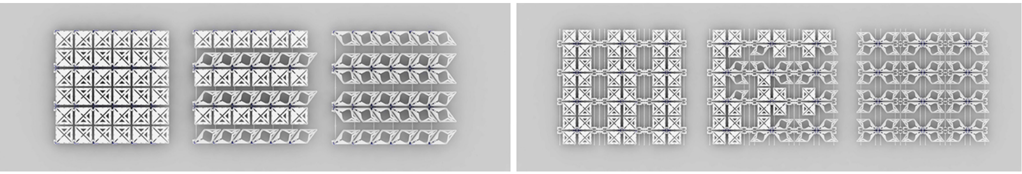


Figure 8
Digital studies in Rhinoceros of the kinetic component assemblies' geometric and esthetic qualities, arising from the changing porosity of the kinetic surface

onto an entire building skin, as a kinetic daylight-regulating collective. The basic component was therefore replicated and arranged into two different compositional variants of façade shields. These models were used to verify the esthetic appearance of the façade compositions, in three circumstances: when the assemblies are closed, partly open and fully open (Figure 8).

In the next development phase, each fully open variant was analyzed computationally, using the Diva software. The detailed goal became to check how the two compositional variants perform in comparison to each other, and in comparison with a low-emission and electrochromic glazing, in terms of the UDI (useful daylight illuminance) parameter, for a radical location case: a south-facing façade of an office building in a climate with high summer temperatures (Houston, USA was the hypothetical location picked for the analysis). Through this, we wanted to confirm a claim that equipping the façade with our kinetic shading devices is more effective than using high-performance glazing, since the kinetic shield is able to actively take advantage of daylight, hence reducing the need to use artificial lighting in the interior.

The computational analysis which followed confirmed that both kinetic variants perform better than the low-emission glazing (the mean UDI ˜ 48%) and electrochromic glazing (the mean UDI ˜ 51%). Moreover, the analysis indicated that the two kinetic variants do not drastically differ in performance from each other (Figure 9; for variant a the mean UDI was ˜ 71% and for variant b ˜ 69%). This has led to the conclusion that both kinetic variants are valid for further development. Ultimately, variant a was chosen to be investigated, due to its greater structural simplicity.

Next, the testing of the responsive behavior of that variant was performed, using the interactive prototyping tools. We employed the Arduino microcomputer, which we controlled using the Firefly programming node. The servo motors and photocells were then mounted onto the 3d printed physical mockup model. The program let us couple the photocell readings with the rotational movements of the servos (Figure 10). This interactive model provided further information on the structural stability of our kinetic system, revealing that the designed configuration, despite the already made amendments of its structure, still tends to be unstable.

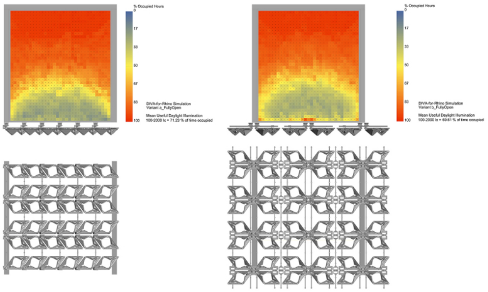


Figure 9
Computational analyses using Diva of the UDI (useful daylight illuminance) for the two variants of the responsive kinetic façade in the fully-open state, indicating minute differences (˜ 2%) between their performances

The above conclusions have led to the decision to create another design option for the kinetic system, based on similar movement principles, but simplified spatially to eliminate the large number of rotatable joints, which caused the previous model's instability. The concept development process was again executed using the visual scripting editor Grasshopper, which allowed us to create an associative parameterized model, in which we could have precise geometric control over the kinetic component assembly. This time, because the focus was primarily on the improvement of the mechanical as-

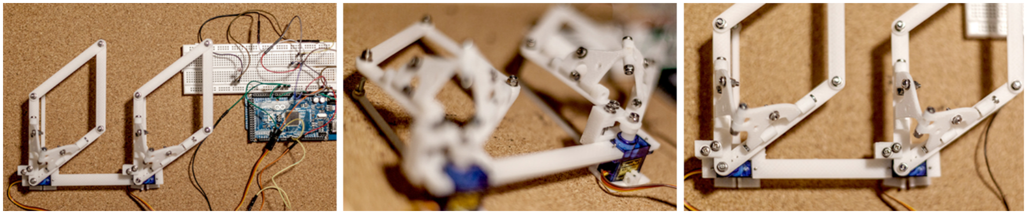


Figure 10
Exploration of the improved 3d-printed interactive prototype, using Arduino, servomotors and photocells as tools for obtaining real-time conceptual design feedback on the kinetic, mechanical and responsive properties of the concept

pects of the system, the concept was prepared in a more specified form of a mechanical model. The digital model was 3d-printed, assembled, equipped with servomotors, and activated, to verify its anticipated structural and mechanical properties (Figure 11). The physical testing of the mockup confirmed that the new treatment of the structural framework underlying the kinetic system, together with the simplification of some of its components, increased the stability of the entire system.

At that point, we terminated the experiment, since enough evidence was gathered for the purpose of the study. Nonetheless, we could imagine that the concept development process is continued further, using our framework and its hybrid toolset. The next point of focus could be the improvement of the new system's esthetics. For example, the visual appearance of the paneling elements, joints and the underlying structural framework could be fine-tuned, and the different ways of an elegant embedding of the servo motors and daylight sensors within the entire spatial system could be examined. The daylight-transmitting properties of the geometric design could also be further calibrated, by using perforations in the selected component panels as a means to more efficiently regulate natural illumination of the interior shielded by our kinetic system. For this purpose, a computational analysis-driven process of component perforation distribution could be employed, in which the daylight analysis results' from Diva could drive the evolutionary optimization algorithms in Galapagos or Octopus, and place various arrangements of kinetic panel perforations in the most favorable locations on the façade.

THE RESULTS OF THE EXPERIMENT

The analysis of the design workflows registered in the design protocols of the experiment indicates that when we applied the framework over the four main phases of the development of our concept, we could freely choose a number and type of design aspects for our explorations, out of the available six ones. In the first phase, a triad of form, kinetic behaviors and system mechanics was investigated (Figure 3a, scheme I); in the second phase, a duet of form and system mechanics (Figure 3a, scheme II); in the third phase a duet of form and performance (Figure 3a, scheme III); and in the fourth phase, a triad of form, system mechanics and responsive behaviors (Figure 3a, scheme IV). It was possible for us to tackle these

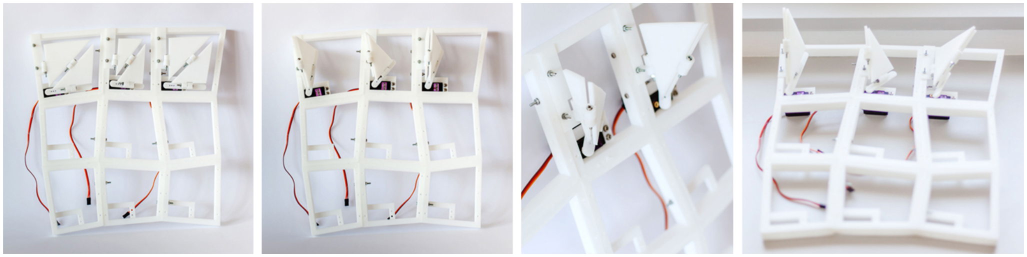


Figure 11
The 3d-printed interactive prototype of the second, more stable variant of the kinetic system

aspects in the design analysis, synthesis, evaluation, modification and decision-making loops, in any order which we found suitable at a particular concept development stage. We were also able to revisit each aspect as often as needed. For example, form was revisited four times, system mechanics three times, and the remaining aspects only once.

The hybrid digital toolset which we applied in our design experiment enabled us to carry out a wide variety of activities, supporting the exploration of the responsive architecture's design aspects and the gradual development of our concept. For instance, thanks to the existence of the parametric modelling tools (Grasshopper) and dynamic physics simulation engine (Kangaroo), it was possible for us to conduct explorations of kinetic behaviors of various alternatives for our façade compositions already in the digital space, before producing the physical models (Figure 4). Owing to the computational analysis tools (Diva), we were also able to compare the environmental performance of the concept variants (Figure 9), which allowed us to make a conscious decision regarding which variant is suitable for further development. Due to the presence of the materialization tools (laser cutter, 3d printer and interactive Arduino kit), we could also observe how our structures present themselves esthetically (Figure 6) and how they behave in real time, within a dynamically-changing daylight environment (Figure 10).

The analysis of the design content produced in the experiment indicates that a considerable number of artifacts was generated and explored, with a total number of 18 objects, out of which 14 were digital and 4 were physical. Those artifacts are diverse, i.e. they have varying levels of abstraction (from general to concrete) and miscellaneous explorative functions (form explorations, esthetics, composition, environmental performance analysis, kinetic behavior simulation, system mechanics proofing).

CONCLUSIONS

The results of the pilot experiment suggest that the framework has two features which could account for its suitability to support the complex task of creating early-stage concepts of responsive kinetic structures. Firstly, the framework introduces specific design workflow organization conditions, which allow to freely (i.e. in an elective order and in diverse configurations) but at the same time also systematically (i.e. within pre-established conceptual borders) explore six design aspects of responsive architecture: form, functionality, performance, kinetic behaviors, system mechanics and responsiveness. Our experiment results indicate that the number, type and configuration of aspects considered at a certain point of the design process can vary from one design phase to another, which leads us to believe that the framework should also let other designers execute their creative workflows individually and freely, depending on the particular needs. This makes us suspect that the framework could be useful for a variety of design situations related to the creation of responsive structures. In other words, we suspect that although upon the application of the framework to different design assignments the configurations of the six aspects explored by designers will differ, and therefore the paths of exploring the concepts will also alternate from project to project, the framework will still remain a valid and useful guidance system supporting these explorations.

The second discovered feature of the framework is that it introduces specific tooling conditions (i.e. the hybrid toolkit of software and hardware), which help to explore the six design aspects of responsive kinetic architecture using diversified means: parametric models, digital simulations, computational analyses, physical models and interactive prototypes. Although this still requires full empirical verification using a larger number of cases, in our pilot experiment the varying character and a large number of generated artifacts could perhaps point at the fact that the framework's toolset could stimulate designers to consider a design solution space which is broader than usual. This in turn could lead towards explorations of a larger number of interesting and unplanned design alternatives.

This promising initial pre-evidence on the framework's properties will now form a springboard from which we will seek to substantiate the abovementioned conclusions with a larger amount of empirical evidence. We will carry out further experiments, aimed at: confirming the features of the framework, assessing its performance in various design situations, determining its advantages and limitations and obtaining clues on its future development paths.

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