Model Translations

Studies of translations between physical and digital architectural models

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With the rise of the digital in architecture and the availability of digital fabrication tools, the interest in the material aspect of the model has intensified. At the same time, the design space for exploration of material behavior and its design potential has been extended from the physical into the digital. This has resulted in a cyclic set of translations from the physical realm into the digital by means of mathematical descriptions and back from the digital realm into the physical by means of digitally controlled fabrication processes. Despite the availability of more and more computational power and improvement of precision in simulation, these translations from the physical into the digital and vice versa can never be exact (Eco 2006), the translations from the physical model into a digital model and from the digital into the physical are "spaces of instability" (Evans 2000). The current paper explores in more detail this space of instability between physical and digital models, its potential for architectural design, and the central role of the mathematical description in this reciprocal set of translations.

Keywords: Architectural model, simulation, digital fabrication, material computation, material behavior

Cardboard physical model turns into a digital mesh or a NURBS surface that is then 3D printed in a myriad of plastic filaments, stuck together or formed out of liquid resin, which is exposed to UV light in order to solidify. And finally the building is built out of concrete and steel. The translation from physical to digital to process to actual edifice means placing avatars of the same model in different domains. Inevitably discrepancies arise. It occurs due to a variety of factors such as physical conditions and requirements of the space in which model is situated, or intended to be situated as well as material and its properties, actual and simulated. The way a model behaves and interacts with the world, its geometry and structure, its physicality is continuously augmented by the necessary adaptations of the ‘same’ characteristics to different realms.

Models are used to test concept, geometry, structure, they do not merely represent what architecture could be or explain an idea or subjugate to buildings as by-products (Abruzzo et al. 2007). They are often instrumental and generative and contribute enormously to the design process. So when a model plays an active part, its materiality (chosen material, its properties and effects as well as physical forces influencing model’s behaviour) plays an active part too. However, material qualities and their effects are often
an after-thought and are rarely a catalyst for geometry. According to Lars Spuybroek (2010) architectural models are pure abstraction of forms, independent of material notion. Nevertheless, in past years there has been a rise of interest in architectural techniques and production that focus on material performance. Architectural discipline has once again started to form a direct relationship with materials (Schröpfer 2011).

In both physical and digital models and their translations into architectural scale there are interruptions in terms of proportions, structure, and formal geometric performance. This paper seeks to find out how material performance affects geometry and structure and what is lost and gained in this process of adaptation from physical understandings of material properties to digital simulation and back to physical material geometry through digital fabrication.

**Finding form and structure**

"Whether labelled material form-finding, material self-organisation or material computation, designers such as Gaudi, Otto, Isler and others have developed approaches that instrumentalised the complex relationships between top-down (form) and bottom-up (material properties) within the design process" (Nicholas 2012).

Let us look at historical examples of the relationship between a model, its materiality and ensuing form and structure. For centuries builders used to make material models to test structure and for form finding. One of the central structural problems were compression systems, such as arches. Before 18th century they had to be developed through trial and error of successive scale models. In the 18th century due to the interest in this problem of mathematicians, such as Leibnitz, the similarity of compression systems to tension systems became apparent. That allowed to test arches through cable models. The first such model was made by Giovanni Poleni in 1748 when he was asked to analyse the structural integrity of St.Peter’s dome in Rome (Addis 2015). In the 20th century Antonio Gaudi continued the work with cable models, but approached it from a different angle. He was finding form through material models, in his experiments the model’s materiality informed the form of the actual geometry. Gaudi, in his quest to find the structural arch, made a model out of hundreds of threads weighted with sandbags; carefully choreographed interdependency between weight, gravity, and tensile strength generated the approximate form of arches of Sagrada Familia. However, actual buildings are constructed in completely different materials, so, once the form was informed by specific make-up of a specific material, the initial material was abandoned and it’s qualities forcefully imposed on a different one. Another problem lies in that a chain model can perfectly account for a multidimensional gravity field, but not for many lateral forces that occur in any building. There is no documented account of exact translation between Gaudi’s models and Sagrada Familia’s actual geometry, but it is rather safe to assume, that it was not a direct and easy one. Frei Otto was also interested in arriving at form through structural simulation models (Erdinger 2005). "Most of Otto’s analog machines consist of materials that process forces by transformation, which is a special form of analog computing" (Spuybroek 2010). Otto, in his form finding exercise of three-dimensional cancellous bone structure and branching column systems, used a wool-water technique. This involved using tension caused by gravity between woollen threads, dipped in water. In both cases the understanding of material properties leads to the development of form. In case of Mannheim Multihalle, a wire mesh hanging model was made for form-finding by Otto, whereas structural analysis models were developed separately by engineers using different materials and techniques, including a digital model. As final structure was made out of wood, which changes its behaviour depending on scale and exact composition, a lingering doubt in Multihalle's stability remained until after it had been constructed. Engineers designed a test that consisted of hanging multiple municipal garbage bins, filled with water, onto the structure. Multihalle bowed less than was expected and it is still standing.
Model as driver for both geometry and structure can be found in works of Heinz Isler and Sergio Musmeci. Isler was the first one to build structures based on suspension method, where forms for shells are found by hanging and fixating cloth. During the early part of his career, simulation programs capable of analyzing his shells were not existent. Hence, he used physical models to prove the structural robustness and stability of his forms (Kotnik and Schwartz 2011). He first built models for form-finding and then, several iterations of the models were made to test lateral stresses, and finally, the model that passed all his tests would become a building. Musmeci’s work was a quest for unity between structure and form, which led to immense amount of experiments, designed to find an integral structural form. His main focus was mouldable concrete surface structures, he strived to test plastic potential of concrete while minimising material and optimising the form. His approach can be summarized in his own words "the form is the unknown, not the inner stresses" (Musmeci 1979). His form-finding models were based on soap film behaviour and stretched textile membranes. In case of Basento Bridge he built final physical model in concrete, one tenth the size of the actual bridge in order to test his system in authentic material and at a relatively close to final scale.

In terms of expansion of the space of an object, once it starts manifesting in different media, the most significant occurs when multiple factors come into play. When a designer is concerned with creating a structure that performs in a specific way in a specific context, rigorous modelling, as in case of Musmeci, is likely to achieve the goal without much significant (for the goal) deviation between models and building. However, once the spectre of demands that a building must fulfil grows, so does the deviation, resulting in compromise and augmentation of initial design. "It is extremely difficult to carry out architectural design with the self-formation processes. The experiment does indeed lead directly to the form, which in itself has already passed through an optimization model, but a design work can only be seen with reference to the complexity of a building project and to the way the building integrates into its surroundings and into society" (Otto 1990).

The question of scale
Scalability of the structural performance still remains a problem in both physical and digital models and this can be attributed to the difficulty of scaling physical properties in and out. In pure analog models the limitations of the techniques rarely have implication on the structural performance but can have real implication on the proportions at architectural scale. Historically, this problem of scaling was one of the main obstacles in the activation of form for structural purposes. The results of experimental methods of form-finding could not just simply be scaled up to provide proof of structural soundness under various load-conditions. And the underlying mathematical description of the form often was to complex to be handled by hand-calculation (Billington 1980). It was this situation that in the 1930s motivated the founding of institutes with research focused on the question of scalability of structural behavior from model scale to building scale like for example the Instituto Técnico de la Construcción y Edificación in Madrid by Eduardo Torroja in 1934 or the the Model and Construction Testing Laboratory by Arturo Danusso at the Politecnico di Milano in 1935, a lab that worked in close collaboration with Pier Luigi Nervi (Olom and Chiorino 2010). In the same way, Frei Otto's famous Institut für leichte Flächentragwerke at the University of Stuttgart was not only exploring self-forming processes in material systems but also developing expertise in scaling up of the observed phenomena to building scale. An expertise that was crucial in the realization of the roof of the Olympic Stadium in Munich in 1971. This project is one of the last that depended still to a large extent on the use of physical models for the validation of the structural behavior of the roof. In the 1970s, more and more computational methods took over the task of structural validation and replaced the labor-intense use of physical scale models.
Nowadays, when digital model is a dominant form of modelling, the issues of scale have been somewhat alleviated due to the capacity of digital software to imitate a multitude of parameters at a multitude of scales simultaneously. Nevertheless, sometimes the simulation is limited or desired architectural performance comes into conflict with structural behaviour. Sometimes the geometry of a digital, weightless model is forced onto reality.

(Figure 1) serves as an instance of that. The desire to literally translate laser cut scale model into architectural dimensions resulted in the necessity of additional load bearing structure underneath the surface. In scale models the 3D surface was structural, in blown-up version it is a skin. In case of (Figure 2), metal panes are a direct reproduction of surface simulation in CAD model. This representation, when translated into architectural scale, creates an exact replica visually. In computer simulation, the pattern was designed by algorithmic calculations to reduce consumption of memory and time and had structural implications, at architectural scale, it increases time and consummation of material and has no real structural consequence. So, in terms of structural performance and cost-efficiency it could be argued that the translation from model to building resulted in a compromise. On the other hand, polygon modelling that was used to create double curved surface allowed for geometric precision due to variable size and density of panels based on surface curvature. As a result, Dongdaemun is architecturally an example of gain, where digital modelling made possible the exact form that designer envisioned.

**Digital simulation and fabrication**

The process of adaptation between the digital and the physical has been a driver for development since the Renaissance and the work of Galileo Galilei. Driven by the idea of a mathematically ordered world, Galilei replaced the qualitative explanation for the necessity of a specific effect from a given cause, which had been common until then, by the quantitative ascertainment of the phenomenon. For Galilei, the essential characteristic of the mathematical description of natural phenomena is the reduction of the phenomenon to measurable sizes such as lengths, surfaces, volumes, or temporal distances—that is, the quantification of the phenomena (Kotnik 2011).

By using this abstracting approach he was able to express the assumed causality between cause and effect in an idealized form by means of a mathematical function. The logical combination of mathematical descriptions that had been inductively attained allowed him, furthermore, to draw conclusions and make prognoses about the more complex inter-relationships in nature. What Galilei started to establish is a process of simulation of reality by means of a formal description that lies at the heart of our contemporary ability to blur the digital and the physical (Lorenzo-Eiroa and Sprecher 2013).
"The development of digital design is often presented as a threat to one of architecture's essential dimensions: the concrete aspects of construction and building technologies, in a word, its materiality" (Frampton 1995). In the past, computer-based design used to appear to neglect the materiality and its relationship with architecture. Properties like gravity, active force, densities are immanent to materiality of architecture, however, in the earlier days of digital design forms floated freely in the digital space, without any constraint. The only limitations were software capacities and imagination. In the current age of digital design, forms can still float in the virtual space, yet they are programmed to respond to simulated constrains of gravity, weight, force, scale, and material. By coming close to replicating the real world constrains 3D software approaches the ability to redefine materiality and not just imitate it. The process of adaptation between digital and physical could be used to discover ingenious solutions to geometric and structural problems. "Computer-aided material production seems to abolish the distance between representation and materiality, provided that one defines materiality in other terms than traditional tectonics" (Picon 2004).

Technological advances promise new horizons: ‘digital fabrication allows to control manufacturing through design data. Material is thus enriched by information; material becomes " informed" (Gramazio and Kohler 2008). If that is true, we should already be able to design materials, to deconstruct their logic and properties and then reconstruct them. It appears, looking at the work of Gramazio and Kohler themselves that a different phenomenon could be taking place. Namely, that information gets 'informed' by material, its properties and behaviour affect design process.

In (Figure 3) Gramazio and Kohler tried to investigate the translation between the digital simulation and materiality by designing the path along which foam material was projected from a distance. They attained an architectural form out of this process, but rigid properties of foam and its light weight were not sufficiently affected by the force of projection. With this experiment they interestingly take up the initial experiment of Galilei in which he deduced the parabolic flight path of an object based on the deductive interlocking of simple laws of motion. Galilei used this example of the flight path to demonstrate the power of his method and the superiority of the mathematical description over reality. A superiority which is questioned by the 'remote material deposition'.

In (Figure 4) they took the fabrication to architectural scale, changed the material to claylike slurry, added more gravity by increasing distance and achieved a complex and dynamic deposited form. Viscosity of claylike material played an important role in the experiment. In both experiments the process of amassing was judiciously designed and was informed by two different materials, which then were aggregated into two topologically adjacent, yet dif-
different structures. The discrepancy came from material properties. In order to achieve a comparable result with a different material they had to change the parameters of system. While both models were geometrically similar, architecturally they created a gradient from an unstable, light, unitary structure to a wall-like, heavy and stable formation.

Another example of utilising specific material properties in conjunction with specific technique is Monolithic process studies project by Andrew Atwood. He worked with plastic deposition, which is the most common technique in 3D printing. Sometimes during printing a glitch occurs and printer pauses while plastic continues to pour out, thus creating thin strands stemming from the body of the model. That imperfection produced fascinating geometry and motivated Atwood to try and replicate it in a controlled manner. In his studies (Figure 5) Atwood manipulated calibration of material control, fabrication precision and process fidelity through a formal technique of offsetting and material process of layering of plastic filaments on top of each other layer by layer. Atwood designed a custom simulation engine for the purpose of modelling the experiment. This simulation was able to predict the material successes and failures within tolerances acceptable in the framework. Glitches occurring in the printing process were recorded, studied and brought under control in order to replicate the desired geometry and be able to work with it further. In both Gamazio's and Atwood's cases materials drove the apparatus even though in one instance the objective was to automate building process and in another it was a form-finding exercise and an attempt to harness the unexpected by-product of rapid prototyping. The difference between Gamazio's digital model and both physical models is architecturally immense even though all three of them perform exactly the same function. Atwood's process focused on the geometrical difference between initial digital model and its erroneous 3D printed version, which became the goal.

Experiments with materiality
According to Sanford Kwinter (1993), form is an instance of structural stability in a system as it seeks homeostasis, thus all form is the result of growth and resistance, it is the convergence of material and force. We set to explore the implications of materiality on reciprocal translations from digital to physical. There is not a fully fledged hypothesis yet, as experimentation is in early stages. What could potentially be the focus is a technique, involving usage
of performance logic of a specific material and transfer of that logic onto another material. The tentative objective of such material studies would be arriving at a pattern of interdependence between materiality and data (simulation) process. Each following experiment operates at a small scale, with a yet unknown potential at architectural scale. All experiments consist of several stages: digital modelling, import of the digital model into fabrication simulation, additive manufacturing. At each stage specific parameters are changed in order to learn the interdependencies. Specifically, the viscosity of the material, deposition layer heights, speed of fabrication, the ratio of bridge speed to print speed. Material employed is ceramic and method of fabrication is layer deposition, using a modified plastic printer as a universal paste extruder. The first phase was to record the deviations and try and discern the parameters and their combinations that led to them. The second phase consisted of reverse engineering the first phase and exaggerating the determining factors in order to confirm and establish further the pattern of interdependency.

As this research is just beginning, the set of experiments is limited to studying the correlation between geometry, a single material (ceramic) and a single fabrication technique (paste extrusion). What they show, however, is that there is a way to design a specific geometric effect by manipulating not the geometry itself, but the parameters defining its translation into physical domain. Such geometric articulation as achieved in Speed of bridging (Figure 9) or Viscosity (Figure 6) experiments is hard to model digitally and even harder to control.

Analysis of Speed of bridging experiment led to its reverse engineering (Figure 10, Figure 11), which shows the potential of control over such geometries. The next phase of the project will be addressing the way materiality affects structural performance of a model. Once both experiments geared towards form-finding and the ones concentrating on structure-finding are carried out and evaluated, we intent to start applying the results to other materials and processes.

**Conclusion**

This translation from digital simulation to digital fabrication simulation to digital fabrication and back will be documented in diagrams, physical models, and digitally fabricated models at various scales using an array of materials. The essential goal is to study the translational transformations in order to, on the one hand, gain more control over material behavior and conditions of the physical environment, and, on the other hand, allow for materiality to exercise creative influence on the design process. This dual action and its consequences have the potential of being an aide and a tool for designers. A final dissertation will organize and analyze the results of experiments and simulations and attempt to build a comprehensive apparatus that will enable fluent translations between various modelling realms and offer more control over new design processes.

Instead of aiming for increasing complexity and precision in the description of material behavior, therefore, the topological nature of the relationship between the digital and the physical could be used to simplify the geometric description and reduce the amount of information necessary for control. This paper can be seen as a first attempt towards an understanding of the digital as a reduced set of essential information that is used to govern the design development already at the conceptual level. Material is used as an active agent that is not fully controlled but activated and is allowed to compute its position in space through local interaction. Such diagrammatic use of the digital could enhance design freedom and flexibility.
Figure 7
Speed of deposition, Ashish Mohite.

Figure 8
Scale in fabrication simulation, Ashish Mohite.
Figure 9  
Speed of bridging, Ashish Mohite.

Figure 10  
Reverse engineered geometry 01, Ashish Mohite.

Figure 11  
Reverse engineered geometry 02, Ashish Mohite.
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