Manufacturing Material Computation
Materialisation Through Digital Fabrication

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Table of content

Abstract

La révolution annoncée par la fabrication numérique et la production de matériaux dans la pratique architecturale est en passe de changer le design d'une manière significative. Le passage de l'analogique au numérique promet de profondes transformations du processus de conception permettant des rétroactions à la fois dans l'environnement virtuel et celui physique ainsi qu'un continuum d'échange d'information de l'intention à la production. La réingénierie des processus des fabrication des matériaux et de leurs capacités durant la conception peut répondre à la nécessité de renforcer davantage l'aspect performatif et durable des constructions contemporaines. Le *matériau informé* sert de nouvelle méthodologie pour les architectes qui cherchent la création de prototype précis et exact pour la simulation et la production ou, à l'inverse, l'émergence de comportements inattendus survenant pendant le processus de fabrication ou à la fin de celui-ci. Avec pour objectif la fabrication numérique, le processus d'itération peut être introduit dans une boucle de rétroaction qui déclenche l'accélération de mutations 'évolutives' contrairement à la production en série de fabrication standard. Comment est-ce que la ré-émergence de la matérialité de l›architecture peut déclencher un résultat plus réactif et performatif à l'environnement, dans un contexte où la pratique est plus importante que l'idéalisation par la représentation, que la fabrication personnalisée supplante les normes de standardisation manufacturières, et que les environnements informatiques permettent de simuler les comportement naturels?

The revolution announced in digital fabrication and material manufacturing for architectural practices is poised to change the design in a significant way. The passage from analogue to digital promises deep transformations of the design process allowing feedback in both virtual and physical environment and a continuum of information from intention to production. Reengineering the material processes and capacities in design can address the need for more performative building and sustainable practice. *Material computation* serves as a new methodology for architects that seek for precise and accurate prototype of material assembly or, at the opposite, the emergence of unexpected behaviours during the fabrication process or at the end of it. Aim with digital fabrication, the process of iteration can be introduced in a feedback loop that triggers the acceleration of 'evolutive mutations' contrarily

to the serial production of standard manufacturing. How can this re-emergence of materiality in architecture trigger a more responsive and performative outcome from the environment in which practice is more important than idealisation through representation, that adaptive manufacturing supplants standards, and computation can simulate natural behaviours?

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Introduction: Materiality Matters

Advances in computation influence all spheres of sciences including design and architecture. In last decade, the field of architecture has witnessed radical changes in design expression and organisation attributed to computational or programmable logic following the rapid development of software. Hitherto applicable to computer scientist and programmers, the expressions *algorithmic*, *parametric*, and *digital* figure now in the contemporary discourse in architecture. Consequently, the conception of architecture has slowly shifted toward a virtual environment and has gradually been alienated from the question of materiality. In such conceptual digitally driven processes, the formal exuberances are especially prominent and follow the free-form aesthetic of the curvilinear blobby shaped and morphogenetic design. In this context, how can the designer establish a better control for the performativity and constructability, particularly its materiality, of complex design that allows computational explorations?

Due to the ubiquity of information technologies, architectural design and engineering are gaining strength and power over the construction process. Tools are changing as technology extends its quest for performance, efficiency, and sustainable practices. Sharing information and tracing products can facilitate the management of materials as well as design procedures. However, the manufacturing and construction industry has neglected to refine its processes and regulations to face new challenges in term of the rising material consumption[1]. Today, the added complexity (interrelated and integrated systems) has led to an overall decline in the building performance and an increase in our overall energy consumption (Krygiel, 2010). Indeed, resources are becoming scarce around the world and the industry exerts an increasing pressure to develop more responsible practices to cope with this context. The development of design using less resources and a better management of waste production during the fabrication is crucial and inevitable for the years to come.

1 Since the 1950s, the increase of material consumption in the construction industry was more than five times higher than all other industries combined suggested in a report on the American industry. Lorie A. Wagner, "Material in the economy – Material flows, scarcity, and the environment" *U.S. Geological survey circular 1221,* US Department of the Interior, US Geological Survey 2002.

Buildings are essentially material but nonetheless the design process is still focused on form generation and aesthetic based on surface composition. Material considerations are often relegated to an visual choice and engender a widening disparity between materials effects (ornamental) and material productivity (efficiency) with the consequence of decreasing the performativity of buildings. As we know, the choice of material and the methods of fabrication have an important impact on the environment. Designing with local materials, less material and less waste material are all issues that reclaim changes in the actual design thinking. Addressing material parameters at the beginning of the design is a way to reach the performance necessary to cope with this problematic (Borden and Meredith, 2012:1).

Research in design through informatics cannot be thorough without the possibility to extract detailed information in the material realm. Modelling is the new tool that can simulate, both virtually and physically, material conditions in the form of prototypes. Because of increases in the size of robotic machines that produce them, the distinction between a conceptual artefact that informs and represents an idea can be actualised at a full scale with quasi no difference. Consequently, the model digitally produced via industrial machines does not differ from architecture to the effect that the intents and ideas are embedded in the prototype as if it was already a component of the building. Digital fabrication driven by automatized manufacturing systems generates prototypes that can be expressed as informed models. (figure 1) Lisa Iwamoto from IwamotoScott Architecture echoes this affirmation in her words:

> "Initially, laser cutters were employed by architects for precision model making, as for engraving building façades, structural members, and building details. Later coupling these machines with the digital-design software that fostered nonstandard form making and came equipped with commands to redescribe those precision forms through serial sections, designers were soon able to envision how sectioning, as a representational method, could become a building technique (Iwamoto, 2009:13)".

The integration of multiple domains, such as architecture, engineering, material science, computer science, management, and biology, is now inevitable to provide a better expertise and open-source process in the quest for performance. Some schools of architecture have recently embraced this turn and teach structure, programmation and fabrication software as part of their curriculum. "Many of the research processes and subjects [...], including acquiring knowledge of architectural geometry and digital enabling skills, is already part of the agenda of the leading schools. Fabrication labs in education which were rare even just a few years ago are

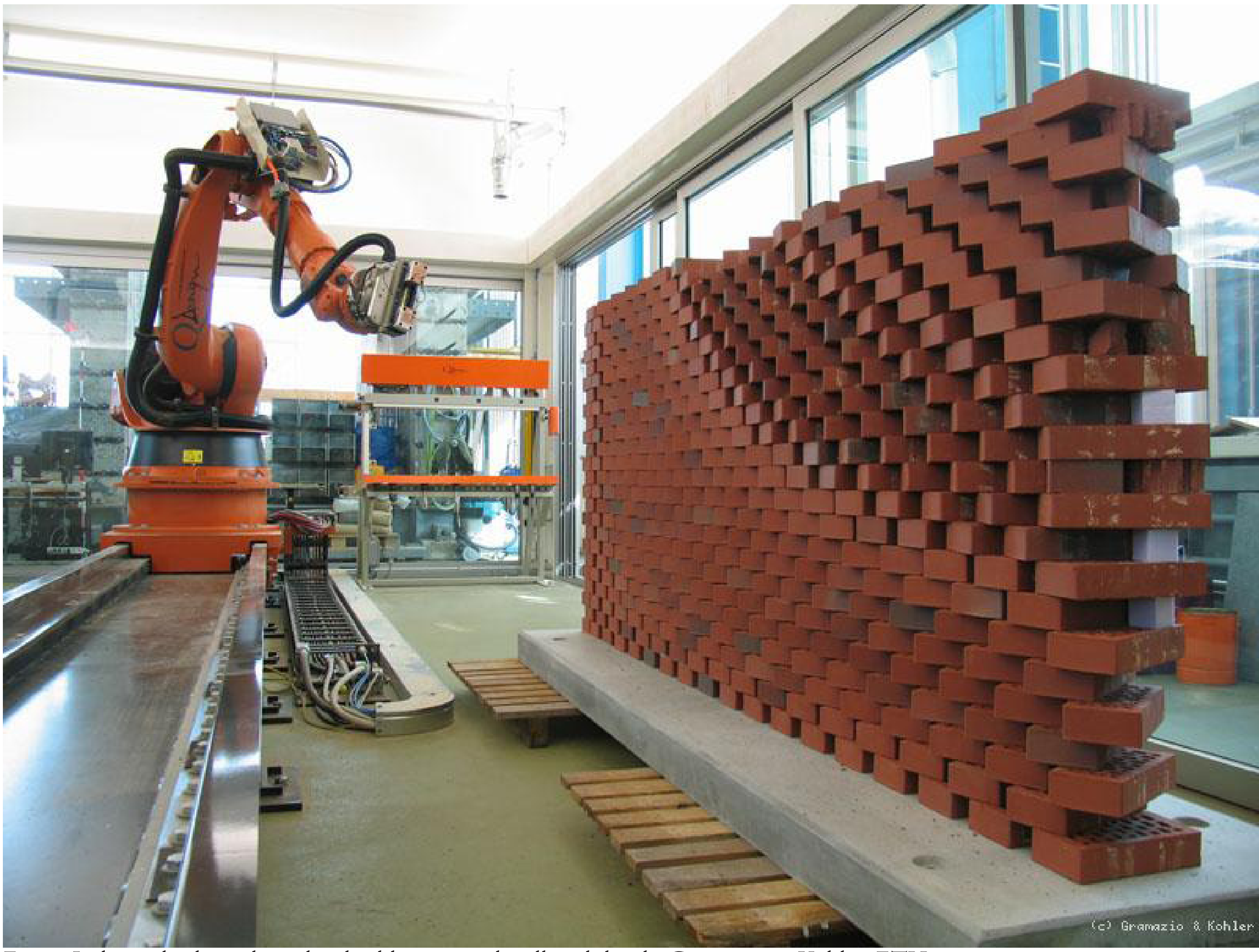


Fig. 1 Industrial robot adapted to build sequential wall with brick, Gramazio & Kohler, ETH.

today commonplace (Oxman & Oxman, 2010:23)".

Robotics systems in fabrication have found their way to deal with this complexity and have the potential to reinforce and exacerbate material properties. In regard to the duality of virtual and physical realm created by the mediation of information in digital processes, digital fabrication opens new perspectives for physical experimentation throughout the research in design. Research in automation shows that the revolution that leads to the implementation of personal computers is now undergoing for fabrication and prototyping, which will lead in the future to a more accessible way to build (Gramazio & Kohler, 2008:9). How can we develop a method of conception that allows by the same way the construction of building? Is this the end of crafts or the beginning of a digitalised crafts where the skills are transfer to industrial robots? How can robotic systems of fabrication be implemented through the process of design in architecture to generate a highly informed materiality? Is there a technique or more used in the manufacturing industry that can be applied to the process of fabrication? How can the virtual modelling be directly sent to an automatized fabrication in different scale including the one of architectural building? As Martin Bechthold, professor at the GSD of Harvard expressed:

> "Initial academic research has tended towards producing non-standard assemblies using normative construction materials, and fabricators are also beginning to deploy industrial robots. Major challenges exist on the software rather than the hardware side. Controlling the many arms and movable elements of a robotic manipulator involves challenging issues of collision avoidance, singularities, payload restrictions and repeatability tolerances (Bechthold in AD 2010:121)".

The techniques of digital fabrication offer the potential for a real investigation in material engineering and in architectural research and design. Material computation is intricately associated to the development of new techniques of fabrication; those operative techniques generate a novel form of material exploration driven by computational procedures. Materiality matters as it generates a bridge between design and production, the intent and the means, at the moment where in practice the line defining the two sides is gradually blurred (Chaszar 2006:11).

This report investigates the field of material computation under three important aspects: performance, prototypes, and computation. The following chapters will scrutinises the historical background of the advent of material computation as well as emergent tools and methods that seems more likely to provide an answer for the material engineering and construction.

1 Performance-oriented manufacturing

> "By mapping the savoir-faire of construction into a programmed process, we gain immediate control over digital fabrication. From now on, we are no longer designing the form that will ultimately be produced, but the production process itself. Design and execution are no longer phases in a temporal sequence – design sketches do not need to be converted into execution drawings anymore (Gramazio; Kohler, 2008:8)".

Material computation arises from the recent interest for digital design (CAD) and fabrication (CAM), domains until recently restricted to industrial design and manufacturing processes. The development of these methods results from the initial need to generate complete models that would facilitate the transfer of information from modelling to simulations, prototyping, and manufacturing. The examples of the car industry and the aeronautics application of technologies are well beyond those of construction and architecture and demonstrate the capacity to manufacture precision and performance rather easily by embracing the digital tools (Kolarevic, 2003; Woudhuysen, 2004). In architecture, performance-oriented design has, for a long time, been seen as an engineering domain guided by efficiency and rationalisation that has little to do with conceptual organisation of form and functions (Kalay, 1999).

The growing popularity of digital manufacturing, the fabrication of components and object directly from the virtual model to an automatized tool, reveals new practices of collaboration in architectural, engineering and construction domains. It blurs the limits of those traditional fields of knowledge. Following those changes, how can the process of design to fabrication be reengineered under the aegis of performance, or in other word *performance-based manufacturing*?

The notion of *performance* in the discourse of contemporary architecture is becoming increasingly important amongst theoreticians, practioners and scholars. Mostly attributed to the design process (performance-based design through simulation and evaluation), performative architecture is also embedded in the socio-political context and in the manufacturing industry. How the architectural form can be conditioned by the application of performance-based principles throughout the design and manufacturing process? What is the continuity of the notion of performance between culture, design and fabrication? This chapter is tracing back this modern age obsession.

Performance is to operate (Picon, 2008). Before the twentieth century, in the context of a disciplinary society, performance was related to the physical (material) and moral (immaterial) duties. With the emergence of sciences in the political discourse, performance has become a matter of structural and energetic efficiency. Back to the 1950's, important researches in linguistics and cybernetics let a techno-functionalist legacy (Kolarevic, 2005). In architecture, the history of performativity is far more recent. In fact, it dates back to the introduction of personal computers in architects' workshops. One important turning point that positioned performance-based manufacture in the architectural discourse occurred in 2003, the same year that the influential, perhaps controversial, book by Kieran and Timberlake *Refabricating Architecture: How manufacturing methodologies are poised to transform building construction* was published.

PERFORMANCE, PERFORMATIVITY, PERFORMALISM

In October 2003, a symposium held at the University of Pennsylvania, entitled *Performative architecture,* revealed the importance of performance as an emerging trend within the field of architecture. The series of lectures, presented by architects, engineers, theoreticians, and technologists, depicted a wide spectrum of definitions "*between appearance and performance*" (Kolarevic & Malkawi, 2005:3). Even if there was an attempt to reintegrate the concept in the architectural discourse, the description of performative architecture still remains technological and instrumental and thus struggled to bring the issues of sustainability and collaboration.

Five years later, two exhibitions held in 2008 emerge from collaborative research groups[2] involved in computation, digital design and fabrication. The first occurs in Orléans, *OCEAN: Conception performative*, presenting multiple models and prototypes fabricated by, amongst other, Michael Hensel, Achim Menges and Yasha Grobman. (figure 2) In the catalogue following the event, the signification of performance is defined as "the capacity of a material, object or architecture to fill up the duties to which they are vested"[3]. This notion of 'material capacity' will take be cen-

2 Most of the participants and new research groups met at the renowned AA School of London in the Emergent Technologies and design group research (EmTech).

3 Published in French in *OCEAN: Conception performative*. In FRAC (Ed.).

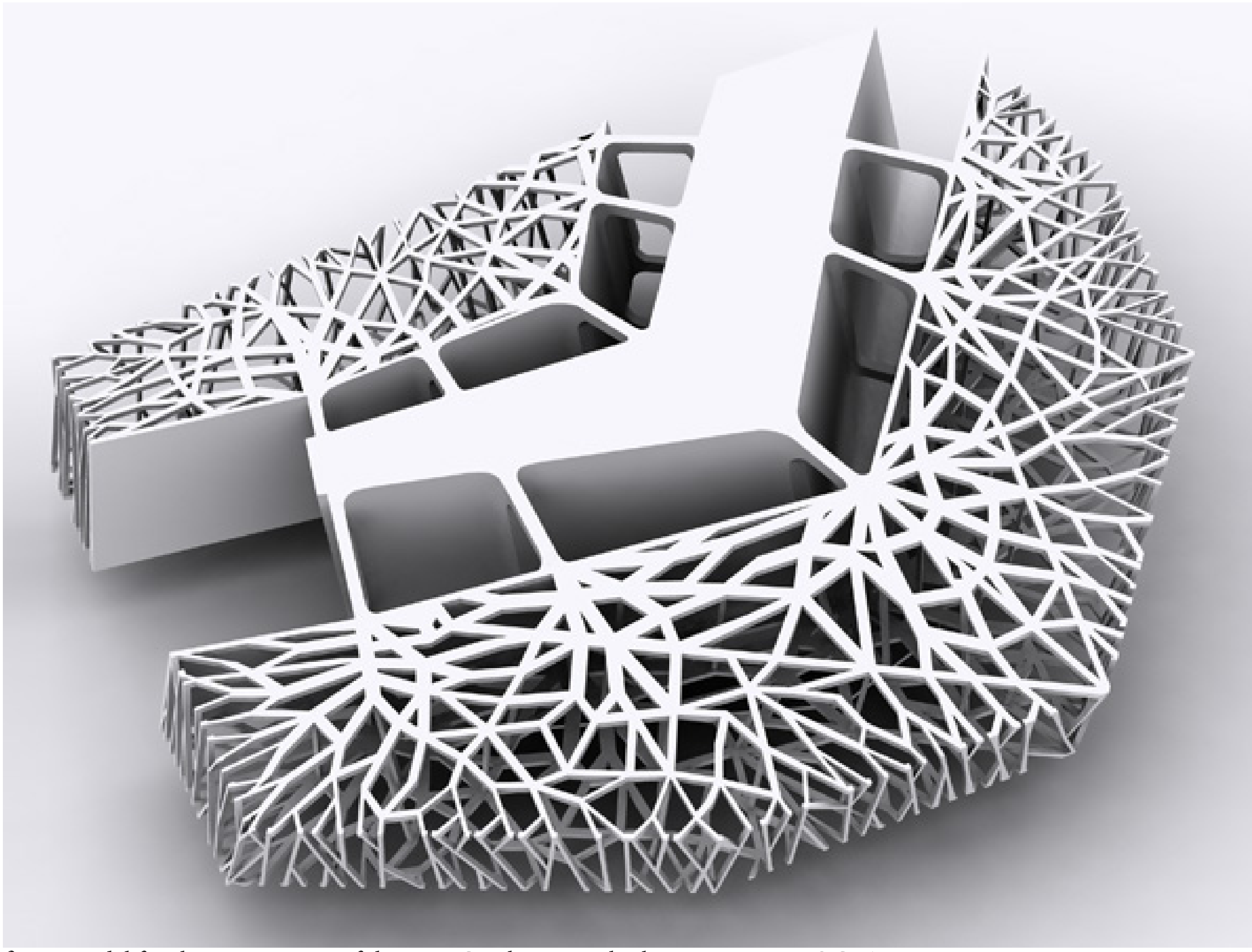


fig. 2 Model for the competition of the New Czech National Library in Prague, OCEAN, 2006

tral for the definition of material computation presented in chapter 3. The second exhibition, *Performalism: Form and performance in digital architecture*, was presented in Tel Aviv including this time twelve architects' groups and offices. Yasha Grobman, a member of the group OCEAN, was curator for the event and the projects of the group, once again, were presented. Together, the presentations of the current work in performativity exacerbated the manifestations, in architectural design, of the prevalence of computational processes in both the design and the fabrication. To perform is to integrate together architectural design, its fabrication and socio-political context. The following text will assess to define the idea of performance in three different sections: 1) the rise of context-based and environment-responsive architecture, 2) the reform of the processes induced by the introduction of digital tools for problem-solving tasks and, 3) the need to reconnect the architect with the

Orléans: "la capacité d'un matériau, d'un objet ou d'une architecture à remplir au maximum les fonctions auxquelles ils sont dévolus."

fabrication process by introducing digital and automation technologies.

ENVIRONMENT-RESPONSIVE ARCHITECTURE

Sociologists and philosophers have pointed out the growing importance of performativity in all spheres of social organisations. Indeed, Jon McKenzie (2001) refers to the age of *global performance* as a new social attitude resulting from the fragmentation of powers and the rise of liberalism. The most persistent values that the phenomenon exacerbates are those of efficiency, effectiveness (Latour 1987) and competitiveness. It tends to redefine the way we measure and define knowledge, in terms of *capacity of change*. This displacement occurred around the 1950's, when the public discourse on narratives[4] decline and the hegemony of the computational theory slowly replaced it (Lyotard, 1984).

The hopes and the hype for performative architecture is driven by the technological advances that are changing and provides new tools by which it seems possible to promote cultural changes (Kolarevic, 2005). Ali Rahim (2005; 2006) from *Contemporary Architecture Practice* explains that performativity is the material, organisational and cultural changes that emerge as a result of a mutual and perpetual influence between culture and technology, that is *catalytic*. Technology is transformative and acts upon society that incorporates it and, in turn, modifies it again (Simondon, 1989; McCullough, 1996; 2004). Technology is social before it is technical (Deleuze 1987).

The product or artefact of a given relationship between human and technology is a craft (Marble, 2010). Digital mediations and technologies are restructuring the means by which design and fabrication produce crafts and architectures. Throughout the last century, labour evolved from human production to tool production and than, to program-based production (Moe, 2010). As the fabrication procedures has become increasingly automated in most of the manufacturing sectors, labour are relegated to the role of operators which means that there is a transfer of skill from the craftsman to the operator, and ultimatly to the designer. Architects, using digital technologies and automated fabrication, are empowered and can perform a more complex design while avoiding most of the risk associated to labour's errors or incapacities.

4 Lyotard define "grand narrative" some epic stories of history such as the dialectics of Spirit, the hermeneutics of meaning, the emancipation of the subject.

The performative approach to building design pursues tools by which it is possible to measure objectively the quality of the design during the conceptual phase, the construction phase and the occupancy (Augenbroe, 2005). Performance-oriented design can be understood as a new pragmatic evaluation of the effectiveness of parameters embedded in the design. Early research in performative design (Kalay, 1999) has shown a vivid interest on the quantitative measure of the effectiveness of a given design through the parameters of satisfaction based on the convergence of the resultant form, the distribution and organisation of functions and contextualisation of the architectural response. McKenzie defined the reduction of performativity to *effectiveness* in architectural design as *technological performance:*

> "*Effectiveness in a given task*. This provides us an initial definition of technological performance. Other terms frequently employed as synonyms of performance are *capability, operation, function*, and *efficiency*. The performance of a technology refers to its technical effectiveness in a specific application or set of application undertaken in a particular context." (McKenzie, 2001:97)

For Kolarevic (2005), this technical approach to performance is reductionist and does not include the embodied expression of cultural traditions and transformations that architecture translates. In fact, the instrumentalism in the architectural design does not constitute the full picture of performativity. However, Picon (2008) sees in the obsession for performance a neo-functionalist movement that tends to revoke any meaning in the search for architectural performance. The main focus for performativity today, he argues, should be turned towards more realistic challenges of the physical improvement and the sustainability of our environment.

Priorities in design are shifting from the consideration of material and labour (as part of the modernist legacy) to economy of energy and resource management (Blassel, 2005; Kolarevic, 2003). The new realism, consequent to the emergence of sustainability, imposes ethical challenges and moral obligations to architects (Kolarevic, 2005). To address this issue, architectural design is restructuring its processes to integrate and perform multiple variables into the design. Sustainability is culturally integrated in the political discourse and drives a considerable proportion of the innovations related to architecture and construction. The resilience of the paradigm forces architectural designers and practioners to achieve more performativity towards the built environment (Hensel, 2006) and their liabilities towards the society (Latour, 1987).

Krygiel (2010) denounces a lack of tools to respond adequately on environmental issues. The added complexities of interrelated and integrated systems that control and regulate our environments have led to an overall decline in the building performance while simultaneously affecting the energy consumption. Blassel (2005) foresees, through a performative architecture, the inevitable convergence of architecture and engineering for two reasons. First, the complexity of a multi-performance analysis and the use of simulation with complete digital models are led by engineers, and second the responsibility and flexibility of the organisation of the methods for design requires architects.

In term of liability, performance-based design is conflicting with building codes and norms that are traditionally a means to evaluate and regulate building qualities (Augenbroe, 2005; Luebkeman, 2003; Malkawi, 2005). Even if it serves to protect the public, the generally prescriptive approach restrains innovation in most of the digital architecture and digital fabrication. With simulation-based and parametric design, performance-based regulations and codes could be developed in order to transfer the responsibility and the accountability in the hands of the designer. The result would allows a building that fits in its environment with the possibility to generate a design that minimize energy consumption (embedded in materials and consumption during its lifespan) and reduce materials used in the fabrication process.

PROBLEM-SOLVING

The reintroduction of the notion of *cybernetics* in the theory of architecture in early 1990's coincides with two majors trends: the generalisation of the use of computer in architectural design and the necessity to facilitate and solve complex interactions (complex physical behaviour and the multiplicity of interactions amongst them) (Malkawi and Augenbroe 2003; Terzidis, 2006; Hayles, 2010). Cybernetics emerges in the late 1940's as the study of systems and structures that involves information flow and the analysis of its behaviour. Along with the development of computer technologies during the same period, cybernetic theories led to the development of computational systems and networks. For McKenzie (2001), cybernetics allows the development of *organisational performance*, based on the values of productivity, tardiness, motivation, innovation, and the ability to establish and fulfill local goals that support the organisation own goals. Its effects on organisations modify the centralistic and rigid approach of traditional management models (similar to the *taylorism*) by encouraging diversity rather than conformity, and development instead of control. In architectural design, the process of information is mostly produced on computer platforms via software to gain time and efficiency, which can facilitate the implementation of decentralised structures and flexible organisations. Nevertheless, the translation from paper to digital have been mainly analogue, only reproducibility and repetition were greatly facilitate.

In architectural design, the traditional techniques of mimesis, representation and reproducibility have proved to be too reductionist and have demonstrated to be incapable to solve adequately the complexity of architectural requirement (Kwinter 1993). Based on the assumption that digitally driven architecture could better respond to complex problem solving, performance-based design offers a more adapted and pragmatic process to cope with the contemporary context (Rajchman 1997). Thus, it is recognized that the style is no longer relevant (Hensel 2010); the performance embedded in the form confers to the form its pertinence. In other words, performance is differentiation and singularity. As Michael Hensel puts it:

> "As discussed above, previous approaches to the relation between architecture and the concept of performance were in one way or another deficient with regards to providing a longer lasting theoretical and methodological framework for research by design and to addressing the increasingly complex demands towards architecture that itself is becoming increasingly reduced in its relevance vis-à-vis the making of the built environment at large. If architecture is thought to deliver more than mere formal styling, we need to start anew in approaching the development of the notion of performance to identify a different potential for its relation to architectural design (Hensel, 2010)".

The notion of style is conflicting the paradigm of performativity in architecture. The complexity found as environmental (i.e., physical, programmatic and economic) is what drives the design, and there is no need to add another layer of complexity in order to achieve efficiency. As Woudhuysen notes:

> "Contemporary architecture is often gratuitously complex, regardless of the ability to deal with the explosion of variable (…). This gratuitous aesthetic makes a virtue out of the chaos of on-site construction. It increases the number of drawings that are required to coordinate critical interfaces and thus diminishes the time architect can devote to perfecting and testing each interface." (Woudhuysen, 2004:223)

In turn, Kalay (1999) argues that the process-based design, whether it is inductive or deductive, is incapable to fully introduce contextual parameters in the dialectic of form and function. The famous motto *form follow function* is a causal relationship that a certain type of function should lead to a predetermined form or style. Performance-based design tends to determine a specific context in the first place without any presupposed form. Instead of deduction, the form finding is process through heuristic iterations.

Performative architecture, as mentioned, is devoted to solve complex problems. To realize the task, the use of algorithmic protocols (Terzidis, 2006) can offer an accurate solution quickly, if the program is properly used[5]. Non-linear processes (i.e. heuristic processes using feedback loop as a tool to learn and solve problems after several iteration of the same action) are used in the industry and in research to optimize or maximize one or more element(s) in order to offer a valid answer to a given problematic (Schwitter 2005). Rahim (2006) shows that the notion of feedback loop is *catalytic* in the process of design. Performative design is generated through a series of transformation and iterative generation of geometrical model, simulations and optimisation that produce the most performing form based upon specific physical conditions and considerations.

Still, the use of algorithms to produce digital design is not always a proof of performativity and can easily degenerate to a mere decorative object. As Kaijima and Panagiotis (2008) suggest, there is an "increasing trends in architecture to exploit the ability of algorithmic design to produce complex forms by implementing relatively simple and easy formulas. This often results in the addition of unnecessary layers of complexity". The scripted algorithms used in the form finding for a performative architecture should be evaluated after the process to assure the feasibility and constructability of the model and avoid the risk associated with fabrication, material used and montage.

PERFORMANCE IN FABRICATION

Digital fabrication in construction is a response to the new development in parametric design and performative architecture. Yet, the type of production stemming from a digitally based design is hardly achievable in the regular industry. It remains expensive, luxurious, and, in some case, requires intensive labour (Kieran & Timberlake, 2003). McKenzie (2001) describes this problematic as similar to the shift from *taylorism* to *performance management*. He shows that, to be competitive, the industry must adjust to new parameters: increasingly service-based, globally oriented, electronically wired, decentered, flexible and easily redeployed. To generate

5 Most of the software are already programmed with a user-friendly interface. Only developers and researchers will have to script algorithms to calculate, optimize and produce a specific (unique) problem.

a performative manufacturing industry, it must be flexible and adaptable (Rahim, 2005). Performative architecture, in order to transpose accurately the performance-based model, must be easily communicated throughout the process heading to the manufacturing. The integration of all stakeholders in the process is crucial to assure continuity between digital information and material as proposed by SHoP (2002:8):

> "Versioning implies the shifting of design away from a system of horizontal integration (designer as generators of representational form) toward a system of vertical integration (designer driving how space is conceived and constructed and what its cultural effects are)".

Traditionally, a lot of tensions are generated between the designer and the contractor, as they don't share the same point of view on how a building should be conceived and build. Each part tends to optimise their solution: profit optimum for the contractor and product optimal for the designer (Celento, 2010). According to Whitehead, founder of the Specialist Modelling Group at Foster + Partners, in discussion with Hensel (2006:45), he claims:

> "The designer is in charge of the rehearsal, but the contractor is responsible for the performance. We are limited in what we can build by what we are able to communicate. Many of the problems we now face are problems of language rather than technology."

Performance in the manufacturing process implies a rationalisation of the resources necessary to transform, produce, transport, and assemble. The energy-used for fabrication, but also for the shipping from the manufacture to the site, should be rationalised (Woudhuysen 2004). The number of components and the type of assemblage can radically change the cost of the project. As Krygiel (2010) mentioned, due to the inflation, the specialisation and the complexity of building, the labour cost increases significantly between 1995 and 2005.

To respond to construction and labour problematic, the potential of Computer-Aided Manufacturing (CAM) offers a potential that has recently found many adepts in architecture (Chaszar, 2006). The concept of *file-to-factory* incorporates the new paradigms appeared in non-conventional architectural design and parametric design and address the issue of manufacturability in the same way as industrial design. The model incorporates the whole process of modelling as a means to manage a performative design from conception to fabrication. Also, this model allows more easily a customization of buildings with very few stakeholders (Willis & Woodward, 2010). It is the CAD/CAM integration that features great interests in the operation that will help to visualising, animating, computing, simplifying, organising, generating, measuring, modifying, realising, accelerating, specifying, communicating, rationalising, etc. The simplicity of the process could avoid a series of transfer for modelling and fabricating information, which could also potentially reduce the risk of errors, and empower the designer during the manufacturing (Woudhuysen, 2004).

However, to be able to translate properly intentions to fabrication, a new awareness is required from architects and engineers in terms of feasibility and performativity. The simplification, the geometrisation, and the materialisation of the design are one of the key operations that, through the design, should be constantly addressed and verified. Amongst those operations, the use of *simplification algorithms* generate a delicate operation to reduce the level of complexity by finding the more simple way to optimize the form, within the desired parameters, that take account of manufacturing, assembly and design considerations. Kaijima and Panagiotis (2008) advocate for the *simplexity* of an object to assure a better transfer between file and factory. The concept is an algorithm that negotiates the complexity of computational design by means to find regular patterns so it decreases variation and organises some elements through selection and abstraction. For the firm *designtoproduction* (2008), simplification is a way to find solution for the assembly of parts and the detailing of the material and joints. The method is composed of an optimization (an algorithmic optimization tools that processed a selection of the best constructive, structural, and functional solution with the help of multi-objective 'genetic' algorithms), and of a discretization of constructible architectural components. The most common techniques to tessellate overall forms are *mapping* (using parameter space to produce optimized tiling that simplifies the components in number and shapes oriented to manufacturing or cost effect) and *densification field* (simplify and equalize the stress diagram).

The research in parametric design has provided a good framework to understand the different possibilities for the informatics model to acquire performative traits but may trigger another form of problematic: the material integration during the whole process. As mentioned, it is most likely to link material considerations at the end of the process, when fabrication matters. The true performativity resides in the actual incorporation of information in materially sound structures that reflects the designer's goals. Therefore, it is critical to develop a clear procedure to help decision-making to maintain a performance-based design in the entirety of the process. The next chapter will bring another understanding of the process of modelling according to material explorations with a nascent use of robotics to fabricate prototypes at every stage of the design process to simulate or verify the performative requirements of this approach.

2 Prototypes in material research

> "We are passing from an age dominated by a competence – one realized through techniques of mimesis, representation, and reproducibility – to one characterized by performance, that is, of pragmatics or modelling." (Kwinter 1993:213)

According to Kwinter, theorist in philosophy and architecture, in the article entitled *Soft Systems*, the major transformations in design that occurred by the integration of informatics in the field of design was poised to transform the practice of architecture by deeply reforming the design process. By 'pragmatics or modelling', he found in 'natural' systems a form of organisation that does not separate the internal process, the morphogenesis, with its material actualisation but instead operate in a continuum, a sort of workflow. He claimed a novel approach based on information, i.e. processed in a literal manner, from intentional parameters to material constitution, similar to the natural organisations of development. The morphogenesis, as he claimed, has proved to be the most adapted system that is able to extract informational parameters from inside and outside, and redistribute useful information back into its material constituency. Without interruption and through natural computation, organisms transfer 'softly' encrypted data throughout the process and avoid intermediate stage of representation. In architecture, the traditional representation by drawing constitutes an intermediation, which breaks the process by incorporating a series of codes and symbols proper to a separate system and cause the lost of conceptual intentions through the translation.

Drawing is obsolete in the sense that it adds a layer of operation and fracture the continuity in the process of making. Instead, it is more appropriate to substitute the act of drawing by that of modelling, which is a fluid transfer of information from digital to physical. Architectural modelling by means of digital process is understood here as the embodiment of all information necessary to communicate the intentions to the builder, contrary to a 'cardboard' model that reduce to a conceptual and formal representation of a concept. Most of architects today are using digital drawing and models to communicate their intentions but fails to integrate the whole process of making in their practices for numerous reasons. As Terzidis (2006) mentioned, the relation to the digital in architectural design practice is more of computerisation than of computation: by transferring old habits of representation from drawing to computers, they kept mimicking stages of representation by simply easing reproduction but not production; design and execution are still very segregated phases.

Computation differs form computerisation: computation is about the automation of processes, controlled generally by the implementation of an algorithmic logic while computerisation consists of a direct transfer of drawings from paper to software (Terzidis, 2006). This process is not "metaphors for a process-oriented approach to design, but are concrete sequences of operations, procedures that have to be designed." (Gramazio & Kohler, 2008:10). Building through computational processes allows designer to generate an *operational model.* The direct transfer of this model can only be possible via digital fabrication techniques hence the actual interest in their development. To achieve a process-based architecture, it seems more important to address the question of manufacturability in terms of programs, tools and materials that enable a material actualisation. The generation of a highly *informed model* should not be understood as a virtualisation of architectural design but as a more direct process from design to material. The continuum between representation (or initial parameters) and production describes in digital fabrication a workflow that has no longer phases but several iterative loops in the process of making. Combined with the capacity provided by computation, models are more than mere representations of conceptual ideas. Instead, they operate as powerful tool that fully actualise the concept from digital to material. The informed model that integrates construction expertise into the programmed process completes the shift, in architectural design, from drawing to making (Sheil, 2012), which does not apply to all digital productions. Indeed, as Ingeborg Rocker (2002:11) declares in contrast of Frank Gehry and Peter Eisenman computer-generated designs that separately in conception and fabrication, "'versioning' – a term borrowed from the software development industry and here newly coined for the architectural debate – describes an emerging development in architecture that – linking software configuration management (SCM) and (EDM) – suggests architecture as a processual data-design, as a continuous processing reciprocal convergence of projection and production."

DIGITAL CRAFT: INFORMATION AND MODULATION

The continuum of the process can be mapped as a series of operation or stage distributed in matrices. However, the form of organisation the information for fabrication is descraibed has to be distinguished from the diagramming in a conceptual level of representation of emerging behaviour (Klinger, 2006:89). For example, the matrice developed by FOA for the Yokohama Terminal represents a genesis of form inside the discourse of emergence, but is not discrete information that will serves as an operative sequence for CAD/CAM integration. The matrices that matters in digital fabrication relates to a code for manufacturability, a series of steps that describes the process of making instead of a symbolic code such as drawings and diagrams. In other words, matrices are the design of production, not the design of form (Gramazio; Kohler, 2008:8).

Made possible by the development of computer-aided manufacturing (CAM) techniques, the continuum of information from digital to physical allows the construction of a digital models directly without the need for major translation between drawings and tools. This process not only eases the communication of conceptual intention, it gives more control for designers over the construction. In his seminal book on digital fabrication, Kolarevic (2003) announces that from a single model, architects can design and produce quasi-autonomously. The *information master builder* as he claimed, represents a unified architect-engineer-contractor that act, by fully implementing digital fabrication in the process of design and making, similarly to its medieval ancestor. By doing so, he refers to the master builder from the gothic era whose role was much more extensive than today's architects. "The medieval master builder (architect) used very few models and drawings to test or communicate ideas, relied instead on direct verbal communication with craftsmen, which, in turn, required continuous presence on site, but provided a seamless exchange of information at all phases of building."(Kolarevic, 2003:57) In this sense, the internalisation of information in the process of building produces a particular relationship in constant feedback between the designer and the crafted object.

Traditionally, crafts are the work of artisans, which means the making of an object processes the material with the skills and the knowledge (savoir-faire) to generates a functional shape. The intimacy of the craftsman with the tools and the material (in order) has played an important role in the evolution of objects towards an evermore refined, precise, and performative object. This interaction reveals the importance of the nodal position that occupies the tool or technology in the transfer of knowledge (information) to the material. In fact, *technê* means, in Greek, the study of skill that if applied in a broader sense, includes also the apparatus derived from the synthesis of corporeal operation on the object of study. Tools, machines, and computers, as well as materials and media share the same extension of the craftsman manufacturing (McCullough, 1996:21).

The separation of crafts from art that occurred during the Renaissance has lead to a rapid industrialisation, serialisation, and production of objects beside the most innovative technologies (McCullough, 1996). Contrary to art production, crafts are functional object embedding techniques and cultural knowledge, and can easily substitute manual labour to a programmable machine as primary source of information[6]. The advent of programmable machines and industrial robots in the manufacturing process is closing the loop between conception and fabrication and might opens up to a reconciliation between craft and industrial production; it is what McCullough named 'digital craft'.

The invention of numerically controlled technologies for fabrication, analogue or digital, were required to process complex shapes and patterns that cannot be crafted directly by hands with a high level of precision. The problematic that leads to programmable machines was indeed a quest for efficient, reliable, and economical process to manufacture complex and repeatable objects. Technologies such as robotics and numerically controlled (NC) machines were found because of a lack of possibility to transfer the intension (information) to the matter itself. Therefore, material performances and capabilities are the core for the development of new technologies.

Early cases of integrative manufacturing can be traced in the XIX[th] century in discrete processes such as weaving. (McCullough, 1996:178). Around 1810, Joseph Charles Marie Jacquard invented the universal weaving machine that is to say one of the first analogue computer. (figure 3) Jacquard's quest was to find a way to deal with more complexity in fabric patterns that was incredibly labour intensive. He envisions the automation of the production by implementing a programmable machine for which the 'program' was contained in punching cards (Moe, 2010). The sequence of those cards was forming all together operational matrices able to direct information directly to the machine. The holes of the punching cards constituted a binary code similar to computer's language, i.e. instead of 1 / 0 the machine was physically reacting to *one hole / no hole*. For the first time, the designer was about to conceive by means of codified language of the abstract machine, a simple operational sequence; the design was more directed toward the production, less of the product.

6 The notion of craft has still today a popular image that has been romanticised during the Victorian era under romanticism stylistics as part of a fabricated art. While the industrialisation of the Western world was taking away manual jobs by substituting the work of the craftsman to repetitive movement on machines, the reaction of romanticism was to redefine crafts as arts.

fig. 3 Jacquard loom with punch cards ca. 1840, from Smithsonian NMAH

The system conducted by programmable machines provides a series of repeated operations that allows the complexity and precision surpassing the power and strength of the craftsman, which qualities are at the basis of the definition of craft.[7] These aptitudes are indeed essential for the transformation of materials that constitute an artefact or processed object. For example, the hand, in the process of transforming clay (material) onto a jar (functional object) provides the necessary operations; it is the application of an external force with intention organised in sequences. However, the tool or technology developed between the material/object and the intention (information) will gain with industrialisation and later computation more power and strength, able to substitute all manual labour.

For Gilbert Simondon (1989), French philosopher, the application of external forces

7 The etymology of the word craft stems from the German *kraft,* which means strength or power.

on matter is described as a transfer of information produced by a print of one form on the other. There is no passive process of formation in the evolution of an object but instead a reciprocal transfer of on side the mould (the external force) that will print a tri-dimensional shape, and on the other the material (Teyssot & Lavigne-Beriner, 2012). It is, in Simondon's word, the process of *modulation*. This interaction between form and matter contradicts the hylomorphic principle[8] that implies the inert or passive state of the matter is only transformed by the mould and not in the opposite way. Not only the final architectural object should be receptive to information by the machine also has to be open enough to allow changes without itself. In other words, the material imposes, because of its own internal properties, the modulation of the machine malleability and the later exerts back a force that shapes the matter.

Viewing architecture in such terms leads to the induction of an intensive and extensive information-processing framework that ensures the concurrent actualization and virtualization of the object. It is here proposed under this context to envisage this fusion in relation to the "concretization" of the object, a term introduced by Simondon in reference to the process by which technology evolves as an iterative process from a transfer between the potential of innovation and its physical evolution. For Simondon, the same principles pertain to the production of the technological object and the organism in nature, the latter being the only one capable of consolidated actualization (Simondon, 1989). For its part, the concretization of the technological object defines a similar informational transfer that is engineered in the matter itself.

Applied to the process of digital fabrication or 'digital crafting', the act of modelling an object (the creation of a model) is part of the modulation process that shapes in a non-linear manner, i.e. by a constant exchange of information from the intention to the tool or technological apparatus. Modelling implies an understanding of material responses to the tool in order to provide a continuous flux of information until the end of the actualisation process. In fact, the development of manufacturing technologies has always been in reaction to material constraints and the expansion of digital tools and technologies, including the computer, is part of this development.

8 The hylomorphic principle was developed by Aristotle to explain the distinction between matter (hylo-) and form (-morph). While the matter is conceived as potential in Aristotle scheme, the form will only be able to carry the actualisation of the material.

MODEL AS MATERIAL SIMULATION

Before the use of computer, analogue modelling constituted a form of formal inquiry in form-finding shapes in architecture. The request of such models was to find certain behaviours of material expression through elaborated mechanisms using analogy to simulate natural phenomenon. The Catalan Antoni Gaudi is probably the most famous in architecture to have used chain models to generate catenary vaults with a precise distribution of forces along the structure. (figure 4) This process of modelling used to inform the shape does not serves as a representation of a conceptual model but instead provide an expression of a material behaviour for a complex emergent form. The model is performative and transfers information to the intention and from the material; it actualises the invisible forces present within the system.

More recently, Mark West used soft scaffolding made of fabric to cast irregular concrete beams. (figure 5) The process of creating a supple mould containing a certain set of information, for example tension of the fabric, its disposition along the line,

fig. 4 Reconstruction of Gaudí's hanging model (Tomlow, 1989)

its stiffness and density, that would constrains the concrete counterpart by its own deformation. Those variations in the mould are similarly induced by the material properties in terms of weight, viscosity, and curing period that would affect the fabric deformation by transfer of information. He named the phenomena described as modulation in Simondon's words, in term of a*ctual reality*. The physically transferred information as presented by West is partly heuristic. The goal is to understand material behaviour in the presence of a non-conform fabrication process. Still, the approach is limited to empirical measurements and is largely disconnected from the continuum of information that would trigger the reintroduction of data from the model back in the design loop. As he puts it: "A physical model (as verb) is excellent because, bound as it is in actual reality (AR), it is rich: full of dense information about physical forces and strains, construction sequence and detail. It is very difficult, however, to get quantitative information out of this kind of model." (West, 2008:52)

fig. 5 Beam model formwork and full-scale fabric formwork beam cast, Mark West, 2003
A 1.5-metre (4.9-foot) model formwork used to work out the construction method for a 12-metre (39.4-foot) reinforced-concrete beam with double cantilevers. This mould, made from a light 'rip-stop' nylon fabric, was filled with plaster. Both the model and the full-scale reinforced-concrete beam are formed in a single flat sheet of fabric stretched into the gap between two plywood 'tables'.

Architectural models and analogue modelling provided, before the integration of powerful simulation tools, a form of simulation in real time. The physical model, even in a reduced scale, has the property to react to specific targets and performances. To achieve such precision, the model should only be a selective actualisation of the whole, i.e. a part understood as an abstraction of a specific organisation. For example, Gaudi's analogue model simulates the force of gravity that would triggers the whole building of interrelated towers. His model serves to find the most efficient way to redistribute loads in a catenary shape. Most important, it was a process of form finding at a general stage of design; there was no consideration of seismic forces, wind pressures, light distribution, and so on. What Gaudi's physical simulation provides is similar to a finite element analysis that is now possible to generate at all stage of architectural modelling. Finite element analysis (FEA) is a form of computational simulation that maps along the surface or the members the structural stress provoked by specific loads.

This form of simulation hence only possible via physical models has now been integrated in the computational realm to a certain level, but it seams the answer from both differs. Indeed, computational simulation can only achieve to generate data, which provides a specific portrait of a characteristic in the model but not complete a full material response. It is only recently that material simulation implemented in software was render possible and even with those powerful calculations, the complexity of material behaviour will still require a physical object to test and measure the capacity of a specific arrangement of the matter. In other words, because of the enthusiasm and the need to find efficient use of material, the process of making requires multiple steps including virtual simulations and physical prototyping in order to achieve a high level of performance.

COMPUTATION AND MATERIAL EMBODIEMENT

When integrated into the continuum of information specific to digital fabrication, the simulation process generates a series of selective model that will inform the project throughout the design. In this sense, the passage from analogue models to computational processes reunites the different stages of the process as a result of sharing a model that would accumulate information throughout the design. Thus, within the same framework, it is possible to iterate the model according to performative requirements. However, the actual performance of a model can only have full validation in the realm of a material embodiment; the simulation needs to be realised in both virtual and physical.

The determinism of computational architecture cannot be fully integrated in the material output generated by digital fabrication. As Manuel De Landa (2009) explains: « Hylomorphic [is a] kind of ideal of form that pre-exists its incarnation in actual forms. […] The forms act as a kind of mould. » The virtualisation of the model produces a form of idealisation; an abstract language determines the sequence of operations logically coded. The complexification of the tools to parameterise and evaluate architectural models allows a greater contextualisation of the digital artefact that might behave in a similar way in virtual and actual environments. However, on the other end of the project, when the transfer to concretisation of the information-led project crosses the physical boundary, the model cannot have the same level of determinacy. In fact, digital fabrication can lead to a spectrum of opposed results: (1) the precise and accurate prototype of material assembly, or (2) the emergence of unexpected behaviours during the fabrication process or at the end of it. As Bob Sheil (2012:139) puts its:

> "Through digital manufacturing processes, ideas that might have remained as an experimental *esquisse* in a previous age are being manifested in physical form. They are prototypes of a particular kind; constructs seeking to validate potential that has emerged through computational investigation, deliberate tests that are seeking to narrow the distance between the digital and the material."

The feedback loops between physical and virtual information can be achieved by re-introducing new parameters from the physical prototype that has emerged from the process of fabrication. This form of iteration by selection constitute an acceleration the principle of individuation of an object in Simondon's term because of its 'evolution' in the state of prototype. In other words, Simondon (1989) reveals that an object will progressively adapt, through design, to a more performative organisation and shape. It is the process of innovation that forms a lineage of a similar object that will absorbs each times there is actualisation of the object contextual and performative requirements. In the case of digital fabrication, the process of iteration can be introduced in a feedback loop that triggers the acceleration of 'evolutive mutations' contrarily to the serial production of standard manufacturing. As remarked by Ingeborg Rocker (2002:11-12): "The *repetition of the same* – in the sense of redundant universal prototypical problem solutions – is replaced by a *repetition of difference*, in the sense of a temporary yet concrete problem solving". The principle of individuation of objects as formal units allows the repetition through the variation, in the actualisation process, of emergent behaviours (Deleuze, 1972).

The possibility to extract the projective design from its computational or informational environment consequently through means of robotic production operates directly, in the form of a prototype, an element of conversation that offers a feedback to the designer at the stage of design. This feedback has great implications on the performativity of architectural design by giving an evaluation of its feasibility, especially on the collection of components that would form the assemblage of materials. As Kevin Klinger (2006:88) puts it: "As the digital model is augmented, altered, and improved, the parametric fabrication files automatically update in real-time, giving the designer instantaneous feedback. The feedback loop from making prototypes, in turn, provides additional design consideration of efficient use of materials and machining time or testing variations of skin panel patterning."

Digital fabrication produces a prototype that for Barkov (2010:96) is defined as "an architectural component with both formal and performative characteristics [from which] arises from the specific capacities of a technology when coupled with design opportunity and imagination." Because of the nature of the process, the prototype allows variations and individuation of material components while blurring the limit between computational architecture and material embodiment. Prototyping is the new drawing that, through making, can absorb much more information and lead to greater innovations. The consequent artefact has also the potential to ease the passage to construction by potentially solving technical and material difficulties of specific design and requirements.

As the model tend to be increasingly produced in virtual environments, the physical output does not require translation in representation but can be send directly to production. Prototypes can be realised in a short period of time with the same technology that would manufacture the whole building. It eases the integration of multiple parameters, features and performances because of a continuous flux on information. More, materials can now be designed throughout the process and can generate a new kind of material, digitally driven and informed.

3 Material Computation

> "Computation, in its basic meaning, refers to the processing of information. Material has the capacity to compute. Long before the much discussed appearance of truly biotic architecture will actually be realised, the conjoining of machine and material computation potentially has significant and unprecedented consequences for design and the future of our built environment. (Menges, 2012:16)"

The recently published issue of *Architectural Design: Material Computation* edited by Achim Menges reveals the re-emergence of material in the realm of design, more specifically in computational architecture. Whereas the title reunites two major fields of knowledge for architectural research, the use of the expression 'material computation' poses, however, a question of its application and knowledge transfer. In fact, it includes a wide range of research on material development based on concurrent technologies, whether it stems from material engineering – as it is the case in material sciences and biotechnologies – or it means the new capacity to extract specific behaviours due to the increasingly powerful computational process. How can this re-emergence of materiality in architecture be revealing a specific context in which practice is more important than idealisation through representation, that adaptive manufacturing supplants standards, and computation can simulate nature?

While, for the research in engineering, the expression material computation or *computational materials* focuses on atomic structures, molecular organisations and physical and chemical behaviours of material, the recently hype around generating new material in architecture refers to a different material scale (Addington & Schodek, 2005). Indeed, architecture deals with large and complex organisations, and so is the approach on computational architecture. Material computation aims to reveal properties of materials by investigating at their specificities to organise the built ensemble in such a way that it would stimulate and emphasize specific natural behaviours. (figure 6) In this sense, the integration of material information that are embedded in the living or non-living form allows the actualisation of selected behaviour(s) in the process of design in order to reveal, enhance or suppress this specific behaviours as part of the intention of design. To succeed, it is most likely to use, at the junction of the computational process and the material transformation,

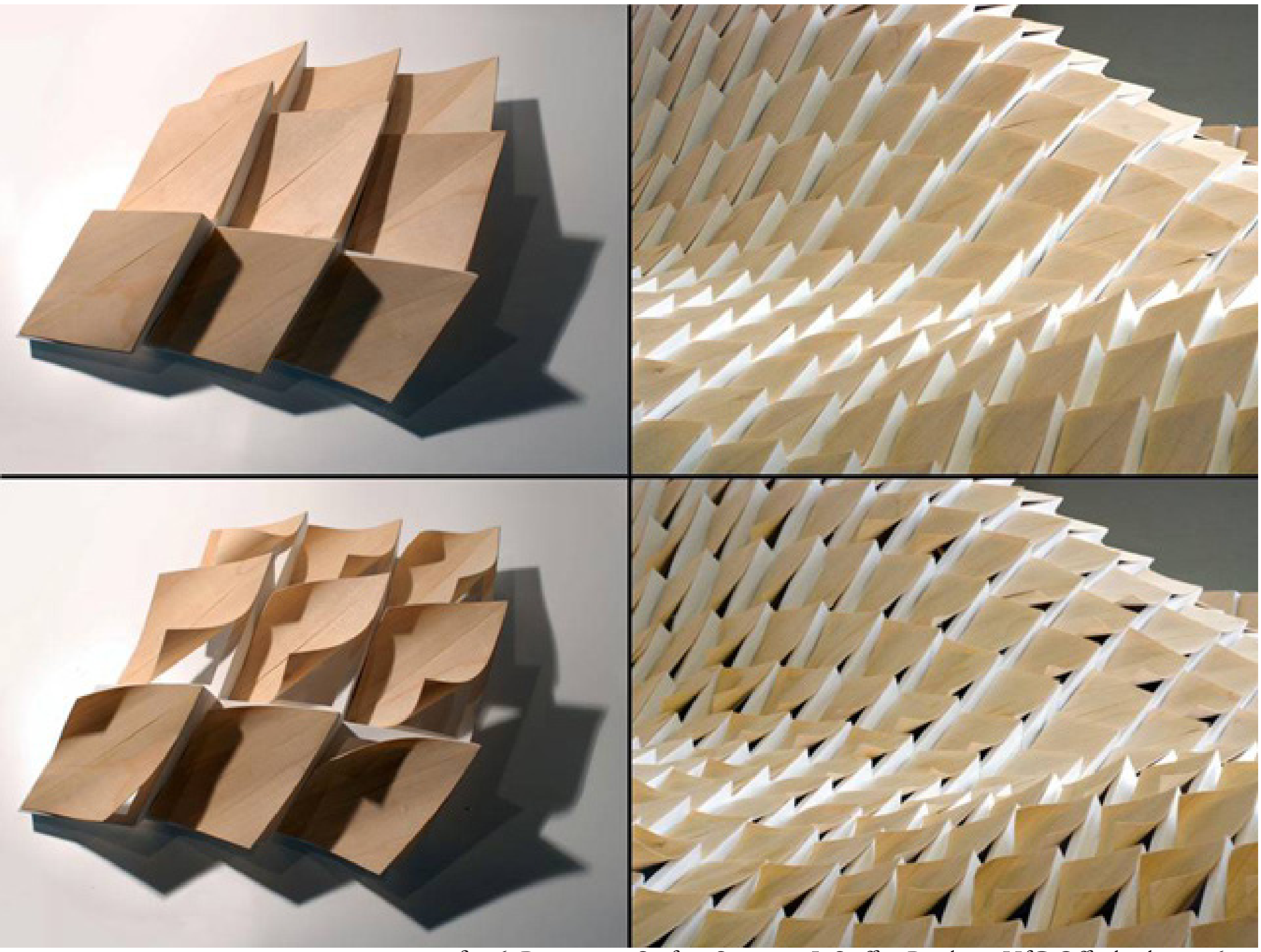


fig. 6 Responsive Surface Structure I, Steffen Reichert, HfG Offenbach, 2006-07

digital fabrication techniques that enable a precise and targeted operation on the material. In other words, material computation is a complementary combination of information from material science, manufacturing techniques, and overall organisation of architectural design.

Already in 2003, Kieran and Timberlake were questioning the fundamental of design processes by asking for the integration of material scientists inside the design team. As an important critique of the 'cardboard' architecture[9] from Gehry and Eisenman, their call for the reintegration of material as a primary consideration in design (aside engineering and fabricating) and fundamental in the role of architects reveals a changing tide for formal plays, especially because of the use of digital supports. The development of new materials, particularly following the WWII, suggests

9 The cardboard architecture refers to a process-based design exclusively dedicated to drawing manipulations, analogue or digital. The eisenmanian grid deformation and the gehrian sketches are mostly famous for this type of formalism.

there is an increasing need to reconsider building protocols and methods of assembly that already has been addressed by the industry, but less likely in architectural circles (Kieran & Timberlake, 2003). Material inquiry for design should not be limited to the effect at the surface, nor to the direct application of industrial standards but a negotiation between material and function. The generation of forms has a direct effect on material selection and the later should play an active role at the first place. The built form is the consequence of a material system, "its capacities (freedom) as well as its constraints (structure)" (Moussavi, 2009:33).

Material computation seems more likely to prevail over formal generation in the first place as a means to fulfil the gap between the mere material selection and material-based design. Material selection operates traditionally at the middle of the process by layering or forcing the most suitable matter for the idealized form. The introduction of complex morphologies stemming from digital computation made this choice less accurate and more difficult to integrate in a traditional architectural process (Chaszar, 2006). The development of *hypersurfaces*[10] forced designer to look towards other disciplines, namely shipbuilding industry and automotive, to find new processes of fabrication connecting information-based design to material constraints (Kolarevic, 2003; Kieran & Timberlake, 2003). Those disciplines have indeed kept a close link between form-finding and material innovation during the same period they embraced digital tools in their process of making.

It is possible to trace such a close system between design and fabrication that is prior to the separation of representation and fabrication in architectural design. Many studies pointed out the relevance of gothic architecture arguing that the close loop between fabrication and material exploration has led to the evolution of formal expression by reducing material needs according to its properties (Kolarevic, 2003; Burry, 2002; Leach, 2002). In fact, the selection of material was the first consideration for the master builder. The entire architecture was based on the specific capacities of stone incorporating the knowledge from stone carvers directly on site to generate the exploration of material possibilities that in turn changed the formal expression. A material-based architecture, similarly, focuses on the material transformation, not on the representation. As Bob Sheil (2012:141) puts it: "The point

10 The term *hypersurface* refers to digitally-derived surfaces highly engineered and information-rich. Marco Novak (1998) explored this relation of computation and surfaces in "Transarchitecture and hypersurfaces", an article published in AD magazine no. 133.

that seems to be in focus [...] is how closely the built work resembles its digital master, and not how the ideas were transformed through making. What is presented in built form, therefore, is an attempt to validate the design enquiry by escaping the exclusivity of paper architecture."

COLLAPSING FIELDS

Since the turn of the century, architectural design shifted from a digital representation to a practical inquiry by looking into material capabilities to absorb computational processes. Unlike the first attempts to imitate biological processes, pragmatic research motivations are directed towards the material end that can provide computation. Evolutionary architecture and genetic architecture helped to define informatics methodologies by pushing boundaries in form generation but did not take into account the material end of such systems. The morphogenesis of the form described by John Fraser (1995) and Karl Chu (2003) in their manifestos represented an analogy to the living systems thus reproduced in codes and processes; the form is generated by information without any considerations to material production as it is for organisms (Ceccato, 2012). Today, "pedagogy has engaged a new literalism of architectural techniques and production that focuses on material performance, to work through the real instead of ignoring it (Borden and Meredith, 2012:2)".

Numerous expressions have shown the desire for architectural theoreticians about material considerations to reconnect with the practical discourse in architecture as a call for grounding architecture in the realm of matter. Amongst them, *digital tectonics*, *new structuralism*, *digital materiality*, and recently *material computation* emerged from the fusion of architectural practice and programmation. In his book *Digital tectonics*, Leach (2002) argues that, following the odd separation of the digital and the tectonic, the collapse of the two worlds is inevitable. Informatics technologies are infiltrating all disciplines and, as they tend to grow in importance, they cannot be denied anymore as distinct tools but as integral to practical application themselves. Digital serves tectonic and triggers advances in the research for complexity in material behaviours. *New Structuralism*, an issue of Architectural Design magazine published in April 2010, exposes under the editors Rivka and Robert Oxman several articles concerning the convergence of architecture, engineering and material sciences that could potentially empower architects to pursue creative explorations in design. As they said:

> "The rise and technological empowerment of these methods can be seen as a historic development in the evolution of architectural engineering. If

engineering is frequently interpreted as the giving of precedence to material content, then the design engineer, in his prioritising of materialisation, is the pilot figure of this cultural shift which we have termed the 'new structuralism' (Oxman & Oxman, 2010)".

Advances in manufacturing technologies for digital fabrication generated an impact for the investigation on material and computational architecture. Similarly to digital tectonics and new structuralism, the claim for an inevitable integration of digital tools within the field of architectural practice and research illustrates the collapse of informatics and materials. More, the expression digital fabrication contains the same opposition, i.e. the application of digital content (information) to the materialisation conducted through manufacturing process. Since industrial processes transform materials used in construction, it is clear that a certain amount of information is applied which in turn lead to a level of mediation has occur through manufacturing prior to conception. "The design application limits of a particular material are no longer seen as inherent within the material itself, but rather as functions of the surrounding processes. Tools and materials have become inseparable and indistinct from one another. There is no material that is unmediated (Borden and Meredith, 2012:2)". With digital fabrication, architects can appropriate the overlap on material manufacturing to extend material-based design by prototyping or generating a *protoarchitecture* (Sheil, 2008). This is what Gramazio and Kohler, researchers at the ETH in Zurich, have explored since 2006 in implementing robotics tools in the design methodology to produce real scale prototypes[11]. (figure 7) They argue that their method is capable to direct in totality the information from the model to the material organisation with a fine precision hardly achieved in actual construction. The result so-called informed material, or *digital materiality* is revealed in their book addressing the same title. As they state: "With the use of digital fabrication techniques, i.e. robotics and engineered processes integrated in the design sequence, architectural design is transforming the material part of design into an informed material (directly through machine) (Gramazio; Kohler, 2008)".

Material computation pushes the concept further in the sense of the integration of information at the core of the material constituency. Driven by the physics of materials, this approach to architectural design reflects the importance to understand

11 The scope of the courses in digital fabrication is to program a formal expression based on a specific material and tool. The full production of prototypes is available at : http://www.dfab.arch.ethz.ch/web/d/lehre/index.html.

fig. 7 The Sequential Wall, ETH Zürich, 2008

the material exploration at a molecular scale. The expression material computation means the integration into the design process of physical computation (driven by natural phenomenon of exchange of information from the environment in a living or non-living system) and artificial processes of conception via informatics (Menges, 2012). Following advances in manufacturing, the refinement of material transformation and production led to more complex material; this industrial manipulation has progressively changed material properties in a broad spectrum covering smart material to composites. As Borden and Meredith (2012) recently states: "Over and above our fundamental socio-economical shift, new fabrication and construction technologies have severed the equally illusory tie between the 'natural', so-called properties, and architectural applications".

Since computational architecture employs scripts to generate forms and components, the introduction of material simulation in the process of design opens up possibilities to control and conceive a specific materiality based on properties and behaviours. Physics-based algorithms and model approximation can introduce the simulation of material, once marginal to form generation. "Such computational processes are based upon enacting physical and material behaviour, such as gravity, drag, tension, bending, and inflation, within a generative modelling environment (Ahiquist & Menges, 2011:82)". The implementation of material consideration a priori in the design process can stress certain goals to provide at the larger scale a more performative organisation. Computing the dynamic specific to the material integrates in the architectural domain the intention to be more responsive of environmental factors such as climate-control, material reduction, stress distribution, and waste control. In other words, large-scale problems in architecture and engineering can be tackled by emergent behaviour programmed preliminary to the form generation.

Unlike the traditional classification of material in architectural design, textures and colours does not figure as important in the first place, unless they are essential to achieve the performance requirements. Material behaviours constitute the most relevant source of variability in material that properties alone do not describe. Material computation finds its application in the way it affects the very realm of its constitution, i.e. the capacity to be affected and vary according to external parameters (De Landa, 2002; 2009). The material stability that is the norm today – the monumentality of architecture – is questioned about the passivity towards their environment. The integration of variables and collateral behaviours in the equation of design opens a totally new perspective for architectural arrangements and place material consideration at the foreground in the process. Designing active materials amplifies relational behaviours with their environment. As Kwinter (1993:224) puts it:

> "At the engineering level – let us leave aside the theoretical/scientific dimension of these developments – we seem embarked today into a world where materials themselves are becoming active shapers of our dynamic environment. This applies at the literal, mechanical level [...], rendering it sensitive and increasingly responsive and cross-referenced with random fluctuations in its immediate environment".

To compute and shape active materials, it is important to transfer adequately what constitute a material behaviour and how to synthesize material information. In his book *A New Kind of Science*, the British scientist Stephen Wolfram (2002:5) exposed the controversy Principle of Computational Equivalence: "that whenever one sees behaviour that is not obviously simple – in essentially any system – it can be thought of as corresponding to a computation of equivalent sophistication. And this one very basic principle has a quite unprecedented array of implications for science and scientific thinking". In other words, Wolfram stipulates that it is possible to claim that all complex systems can be simulated and that the 'natural' behaviours like those of materials are themselves driven by computation. Therefore, to refer to Achim Menges (2012) expression, *material computation*, the behaviours of material can be describe as a digital parameter which in turn will be expressed by the material as a form of analogue computing.

METHODOLOGY

The methodology proposed to design material computation is a reverse processing. The material would produce the from by testing and calculating the potential of the material first and then implemented in a form-finding process that will optimized the values founded (Wilkins et al. 2011). Instead of a process based on evaluation of formal preconception (or idealisation of the whole), the material-based approach investigates the material capacity as the driver for form generation; the material or the parts simulates the form. This bottom-up approach implies to review the methodology in design using digital tools as a means to integrate material consideration at the beginning of the process. The following diagram proposes a logical methodology using material considerations at the beginning of the process based on three important projects on material computation: (1,2) ICD/ITKE Research Pavilion built at the Stuttgart University[12] in 2010, 2011; (3) Voussoir Cloud installation built in the SCI-Arc gallery in 2008[13]. The order of phases in the diagram is not meant to be linear but constitutes a network of interactions stemming from material inquiry to the fabrication.

(1) PERFORMATIVE REQUIREMENTS

The first step consists of gathering information about the requirements sought for an optimal and qualitative design based on *overall goals* and *material behaviours*. It is intimately linked to the material selection in the following step and allows multiple feedbacks between the two but should only define principles that drive the performativity of the potential object. The goals consist of general parameters such as site constraints, climatic requirements, light, waste reduction, local production, and

12 The pavilion was realised by a multidisciplinary team led by Jan Knippers (Institute for Computational Desgn), Achim Menges (Institut für Trag-konstruktionen und Konstruktives Entwerfen)

13 The installation in partnership with the School of Architecture at SCI-Arc was originally a command for IwamotoScott Architecture (Lisa Iwamoto and Craig Scott).

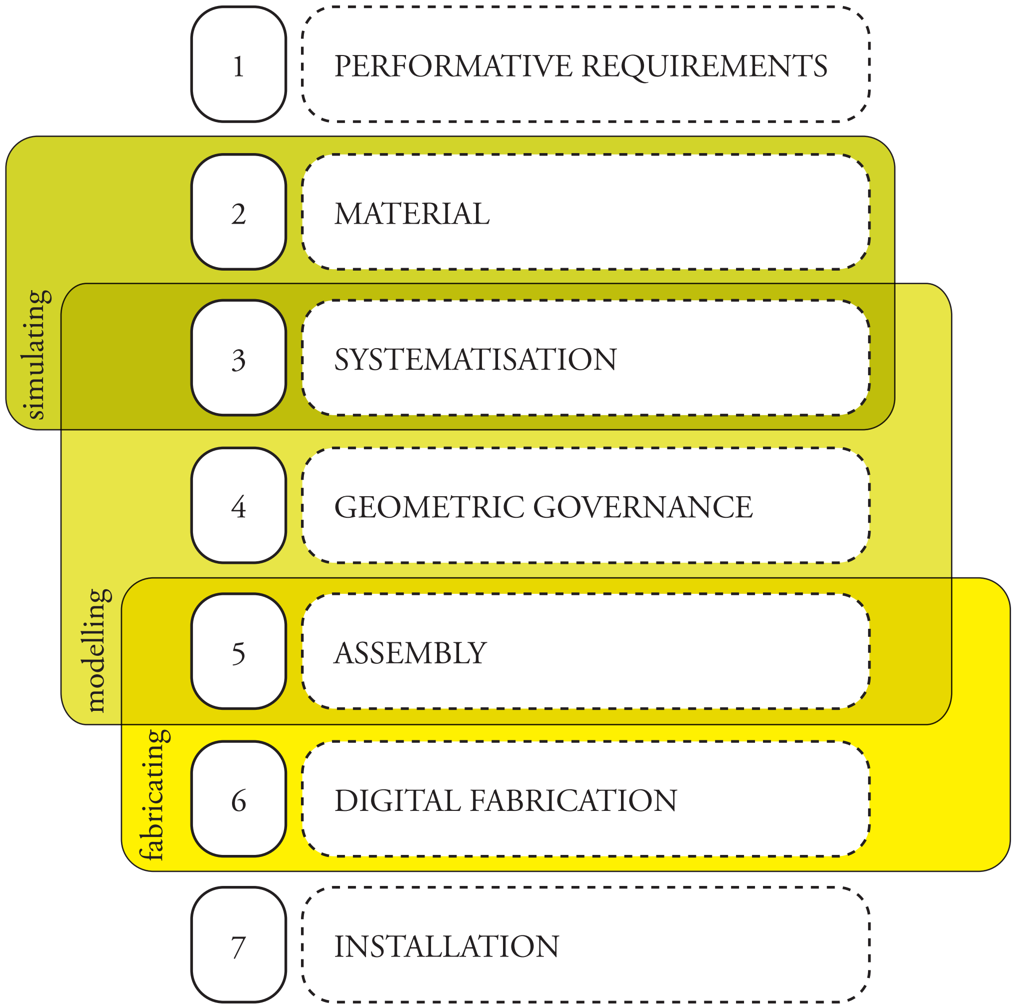


fig. 8 Design categories and overlapping sequences (simlutating, modelling, and fabricating)

functional construction purposes (structure, envelop, etc.). For the material component, the parameters concern lightweight, shear strength, elasticity, anisotropy, translucency, porosity, folding-capacity, etc.

(2) MATERIAL

The material selection can be approached in different ways: through *material categories*, *multiple-material assemblage*, *fabrication process*, and *reverse engineering*. Indeed, the previous requirements can lead directly towards a specific category of material if they are many and then eliminate in the process a wide range of materials. A combination of material may help to realise a multi-performance objective but need a strong link and multiple feedback loops with the fabrication process to interlace adequately the different parts. If the requirements are not defined or offer less or none constraints, a more heuristic procedure can stems from a fabrication process (2.1)

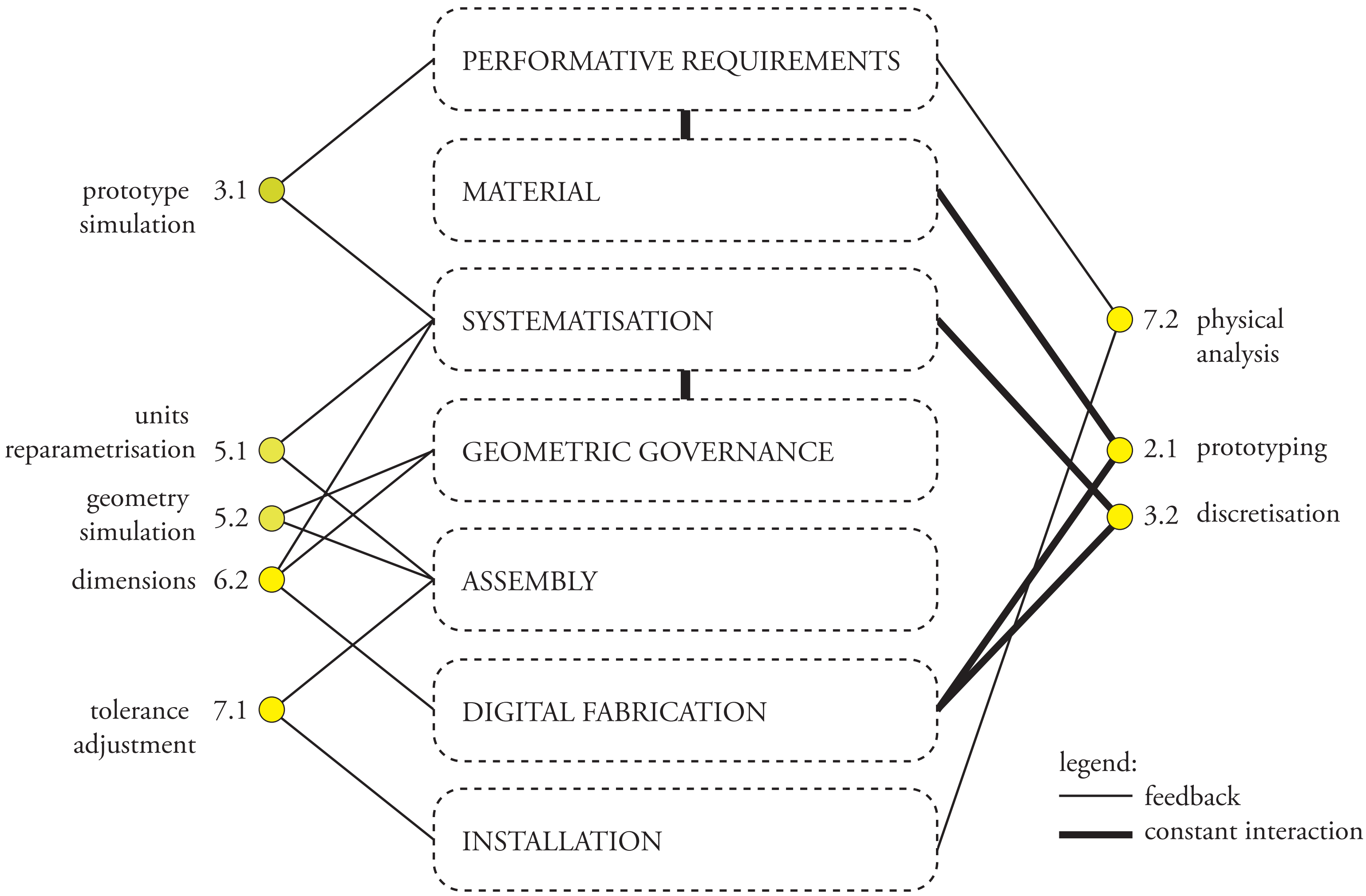


fig. 9 Design feedback loops through virtual and physical modelling

to create new material composition. Another way to lead material performativity is through biomimetic, or reverse engineering, to find specific behaviours by looking to complex structures existing in nature. From natural systems, it is possible to find performative traits that emerge from a specific agency of material constitution.

In any case, the step for material should not constitute a library selection but an inquiry about the molecular constitution, the micro-organisation of parts in the case of heterogeneous materials (for example, fibres and collagen in the case of wood), the variable behaviours towards environmental factors, the stress distribution, the vernacular and contemporary uses, etc. All the factors important to the design will be transfer into informational data within a programmation script for simulation layout and pre-analysis. To compute material, it is essential to simulate the potential of the matter early on the project in order to express the variables that would allow the optimisation of material behaviours.

(3) SYSTEMATISATION

The systematisation constitutes, for material computation, the manner of which patterns emerges from the material self-organisation – biological, mineral, or chemical. According to Philip Ball (2012), "many natural patterns result from mathematical analogies or equivalences in the rules governing their formation – whether these rules are expressed in terms of continuum [...] or as local interactions between components". Patterning is structuring the form from small organisation emerging from the matter. It is a transferable logic of a phenomena or behaviour that the material organisation expresses to a script enabling generative component or units shapes and structures in mathematical expressions as demonstrated by John Von Neumann, John H. Conway and Stephen Wolfram. "It is characteristic of structuring that the static pattern of configurations, tessellations or any form of structural order can be

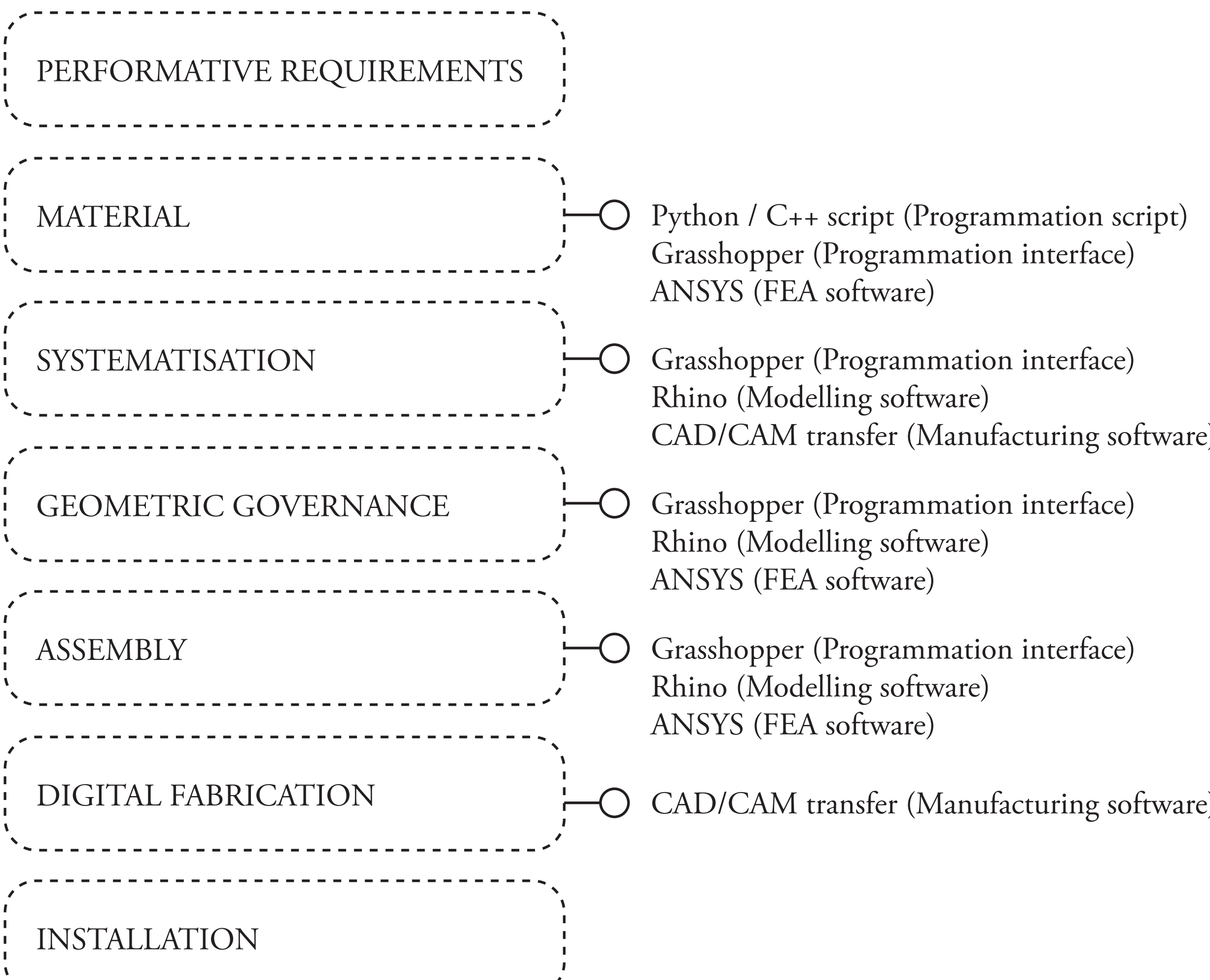


fig. 10 Software requirements for information exchanges

mediated into a system of both generative and differentiated potential. (Oxman & Oxman, 2010:)." It confers to the system of parts a greater degree of freedom for variation and modulation essential to allows targeted local performances of the global organisation. This flexible organisation of tessellation "through nonstandard manufacturing, […] provide an inherent economy of means (Iwamoto, 2009:36)".

The systematisation of material units constitutes a model to reveal material behaviours as a proto-organisation following formal strategies such as *formal structuring* (branching, voronoi patterns, 3D packing, and fractals), *textiles structures* (braiding, weaving, knitting, and interlacing), *surface continuities* (folding, lofting, waffling, panelising, stamping, and punching), and *additive layers* (contouring, carving, and casting) (Iwamoto, 2009; Oxman & Oxman, 2010). Those operative formations of the base unit have global repercussion on the form (4) and on digital fabrication techniques (3.2), the later provoking a constant feedback from tools to strategies to set the limits in terms of feasibility, cost and size. Borden and Meredith (2012) describe a simplified classification of material strategies as *vector* (bone, member, trajectory), *units* (aggregation, chucking, and field effect), and *monolithic* (planes and surfaces with continuous, there-or-not-there integrity).

The stage of unit development is also the first moment to fabricate a prototype in order to simulate the behaviours form the 'digital' material and test its ability to perform the fundamental requirements. This can be realised in two ways: a virtual simulation with finite element analysis (FEA) software and a physically built prototype of a single unit (3.1). Since the transfer of information from virtual and actual reality can be made rather easily CAM/CAD transfer, it is possible to generate an acute prototype for manufacturing early on the process as a tool to explore material behaviour with multiple feedback before setting the final form of the whole assemblage.

(4) GEOMETIC GOUVERNANCE

While units are explored, the geometric governance should influence in parallel the anticipation of the final aggregation, the macro-organisation including *geometric rationalisation*, *functional arrangements*, and *site constraints*. The geometric relationships between parts constitute the most important part of this step and therefore have a certain impact on the unit's geometry and variability. "This is what we call an adaptive building system: a system of parametric components, which are multiplied over the shape of the structure and are adapted to the local geometry (Scheurer, 2008:63)". This methodology using material as the first consideration to the design allows a more flexible formation of the ensemble through pre-rationalisation of the geometry instead of a post-rationalisation. From the units developed with material consciousness, it is rather easy to expand to the overall structure the behaviours of this aggregation, particularly the functional and structural performance of such a system. Ceccato (2012:100) express this in term of co-rationalisation that means "the embedding of material properties and assembly constraints directly into the (parametric) design model at the design stage, such that either the geometric definition of the model or the rules that describe its constructability may be altered in real time within the parametric model". The development of *architectural geometry* discipline witnesses this nascent need for engineering discrete surfaces due to parametric design[14].

(5) ASSEMBLY

Layering and detailing the connections of parts is fundamental to assure a link between model, the fabrication, and the installation. On the methodology scheme, this phase overlaps the modelling and the fabricating groups and describes multiple feedbacks with the previous integration of shapes, units, and material (5.1; 5.2). By intersecting the detailing of assembly in the modelling process allows the possibility to integrate in the shape principles of connections such as *alignment* and *part interlocking*. This is called in industrial design the integral attachment or snap-fit (Sass, 2007) mostly found in older techniques of assemblage in carpentry: *dovetails, slots, tabs, zips*, etc. "A novel approach to assembly found in this research removes the need for secondary assembly mechanics (screws or nails) by embedding the logic of component assembly within the geometry of each component (Sass, 2007: 302)". The level of precision of digital fabrication methods allows generating joints that holds by friction.

For additive manufacturing (known as rapid prototyping), the detailing of part can also include movable parts that are printed in the same time such as *chains, hinges,* and *valves*. Since the additive techniques for fabrication are limited in size, assembly details are equally relevant.

14 One of the best example of the growing popularity amongst designers and engineers in the annual conference Architectural Advances in Geometry (held in Paris for 2012).

(6) DIGITAL FABRICATION

The transfer of the model information to automatized procedures is known as digital fabrication. The production is based on *cutting*, *subtractive*, *additive* and *formative* techniques following the different type of manufacturing robots used to transfer digital information to the machine. This file-to-factory is realised through several steps, many by exporting model files in intermediate information that translate the model into machine movements. "CNC cutting, or two-dimensional fabrication is the most commonly used fabrication technique. Various cutting technologies, such as plasma-arc, laser-beam and water-jet, involve two-axis motion of the sheet material relative to the cutting head, and are implemented as a moving cutting head, a moving bed or a combination of the two (Kolarevic, 2003:33)". A more resent technology for additive manufacturing and rapid prototyping may promise to save time for assembly. Mainly used for very complex tridimensional space structure, research tends to show it will be possible to 'print' concrete (Khoshnevis, 2004), sand, clay and ashes (Rael & San Fratello, 2011), but also polymers (Oxman, 2010; 2012).

Those techniques of manufacturing have limits in term of dimensions and should be validated with a feedback to the unit's systematization (6.1) according to the time to fabricate, the material behaviour and the size of units. As Fabian Scheurer, director of designtoproduction, expressed:

> "Machines that create complex form from homogeneous materials are very convenient and simple to use at a model scale, but when naively applied at full architectural scale, they inevitably reach a point where they lead to both inefficient production processes and overly massive structures. Manufacturing methods are all but scalable (Scheurer, 2008:60)".

(7) INSTALLATION

The installation or montage remains an important part of the process where all the information driven by parametric systems are physically tested (7.2). It is the case for tolerances for each material especially for interlocking parts (7.1). The major concern during the installation of all the components is the labour requirements in terms of time and skills. In addition to the labour, a proper identification of the puzzle-like pieces and a plan for montage are essential to assure the sometimes-complex discretization produced by parametric design and material computation.

This brief description of the proposed methodology offers on reading of the possible organisation from which material computation can be explored. However, this pattern tends to be similar to material-based projects of which material has a greater importance than the shape it generates. As stressed in the chapter 1 and 2 of this report, the multiple feedback loops during the process are essential and in no case this methodology should be reed as a linear process.

Conclusion

The methodology proposed in this report shows the new possibilities offered by combining digital fabrication and material computation to address environmental issues such as material scarcity and waste reduction. Performativity, in the context of organisation and management, coupled with computational architecture has proved to provide an efficient platform to simulate material behaviours but cannot be fully implemented without digitally driven manufacturing processes. The development of prototypes since the beginning of industrialisation and computation, especially in the textile, automobile and aeronautics industries, is an important source of knowledge to make possible to transfer material information directly from the machine to the material itself. More, it made possible to reengineer material behaviour by research in a process of multiple feedback loops.

However, it is not clear that, the use of CAD/CAM procedures for digital fabrication will empower architects but it seems likely to give them broader possibility to act in the construction process regarding to the variation of form and the accuracy of detailing (Chaszar, 2006:11). The complexity resides in the transfer of information through different software that are not always open-source and compatible as well as the need to be able to learn to operate such programs. Also, the potential of such material systems is huge but still requires research to define a cohesive methodology when it reaches the building scale. More, there are many parts of the building constituents that serves practical functions that are highly manufactured – such as windows, doors and so on – and are not addressed by these experimentations in digital fabrication and material derivatives.

The methodology developed upon the new systems of fabrication, programmation, and simulation presents the state of research in material computation. Further developments in computational architecture will need to collaborate more intensively with other disciplines to validate this method in the optic of engineering and programmation and then design predictable material behaviours.

Annexe I

ICD/ITKE Research Pavilion

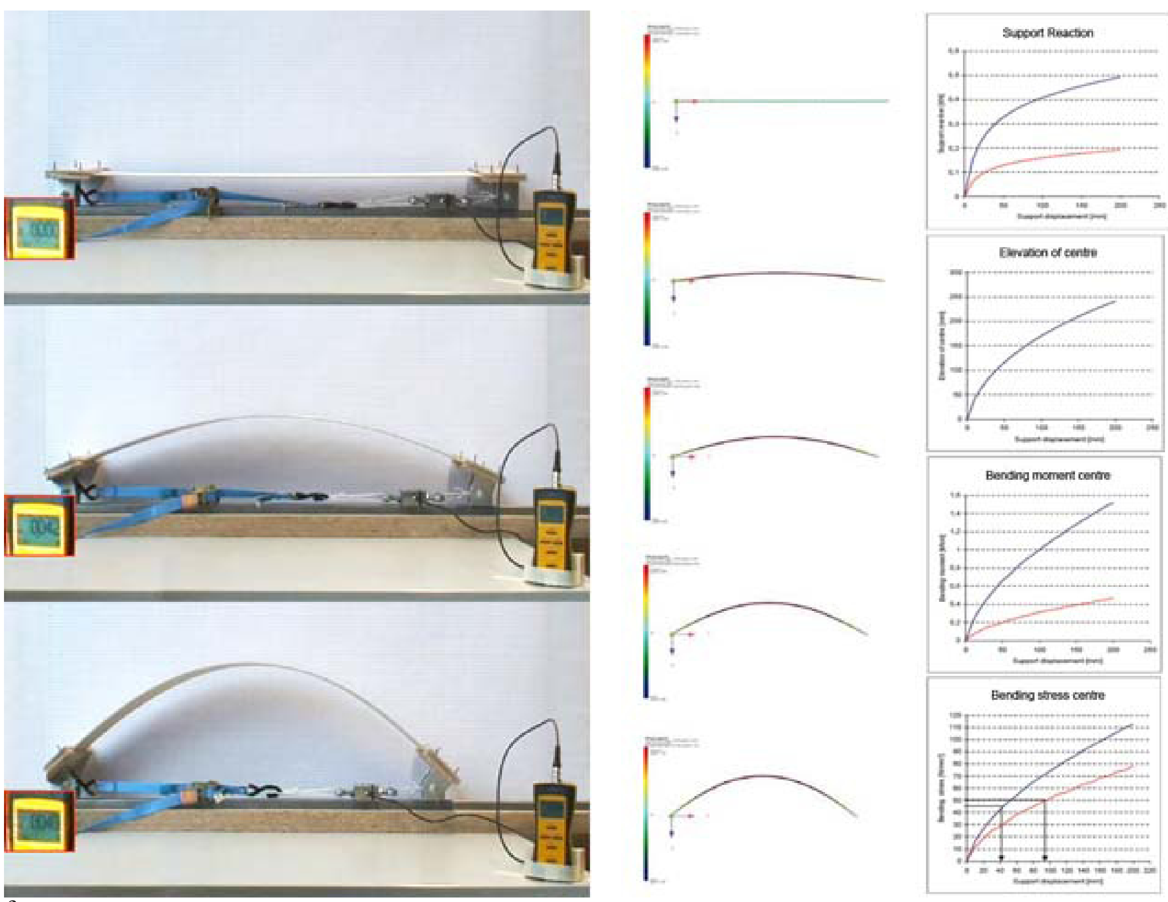


fig. 11

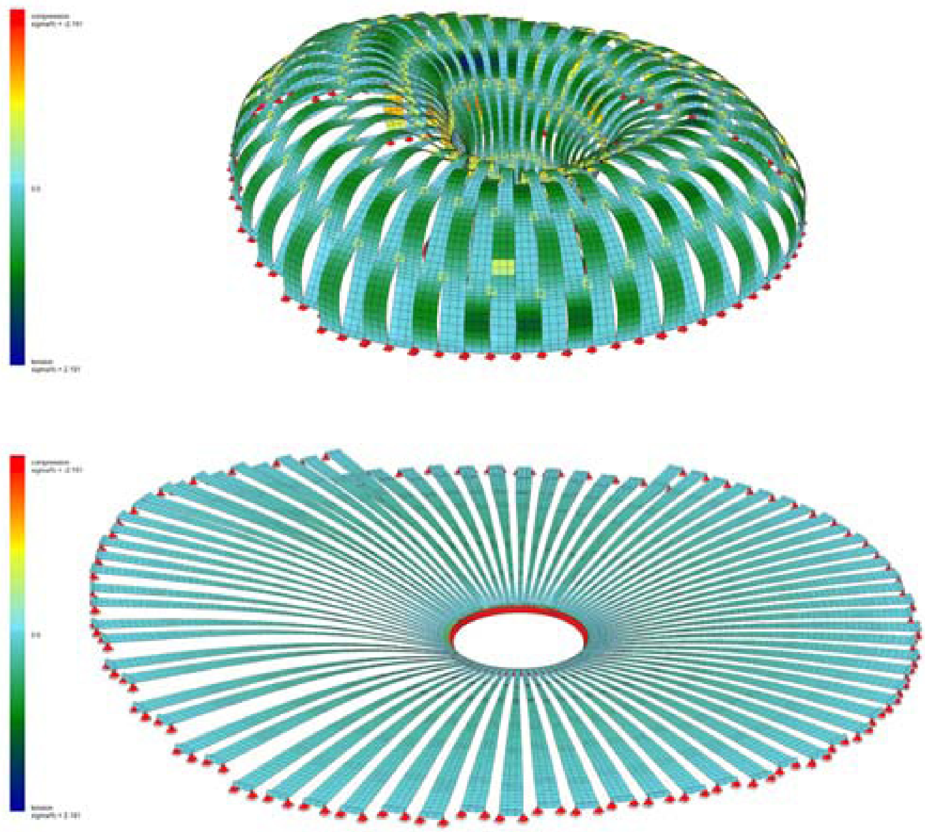


fig. 12

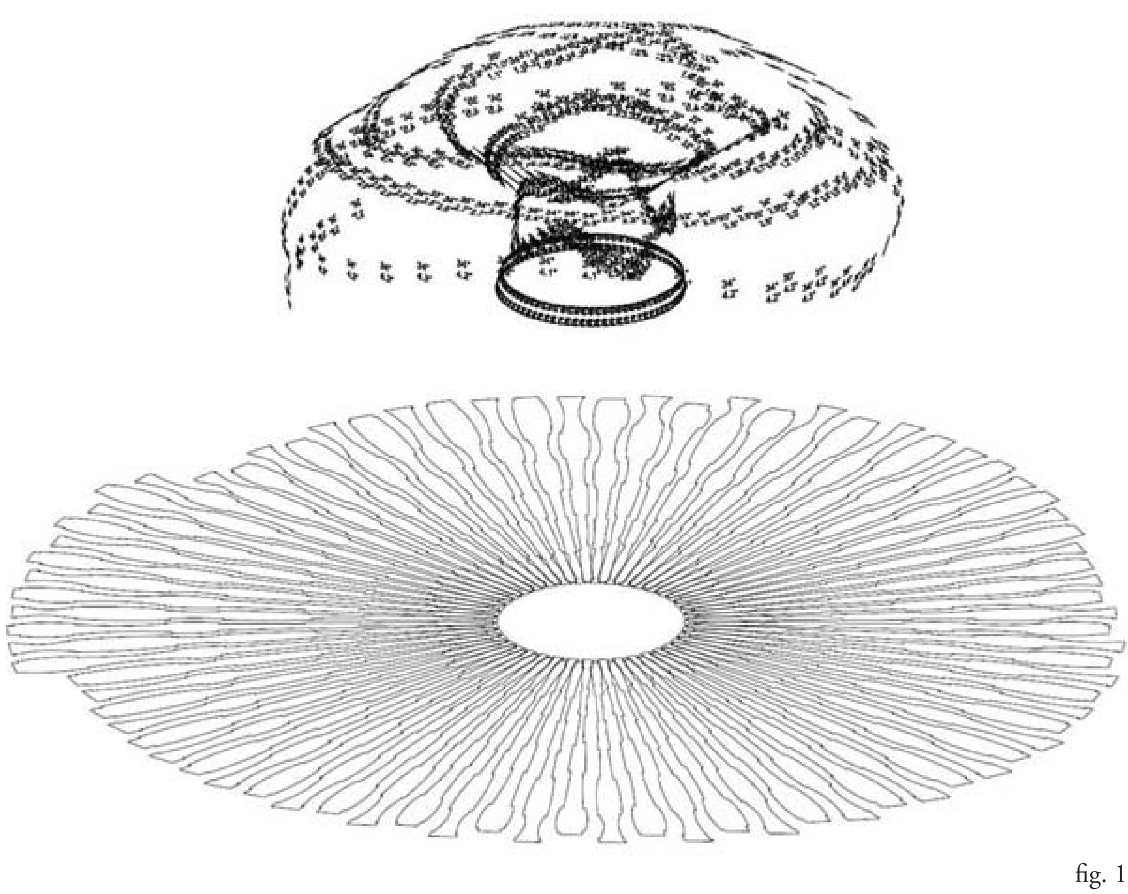


fig. 13

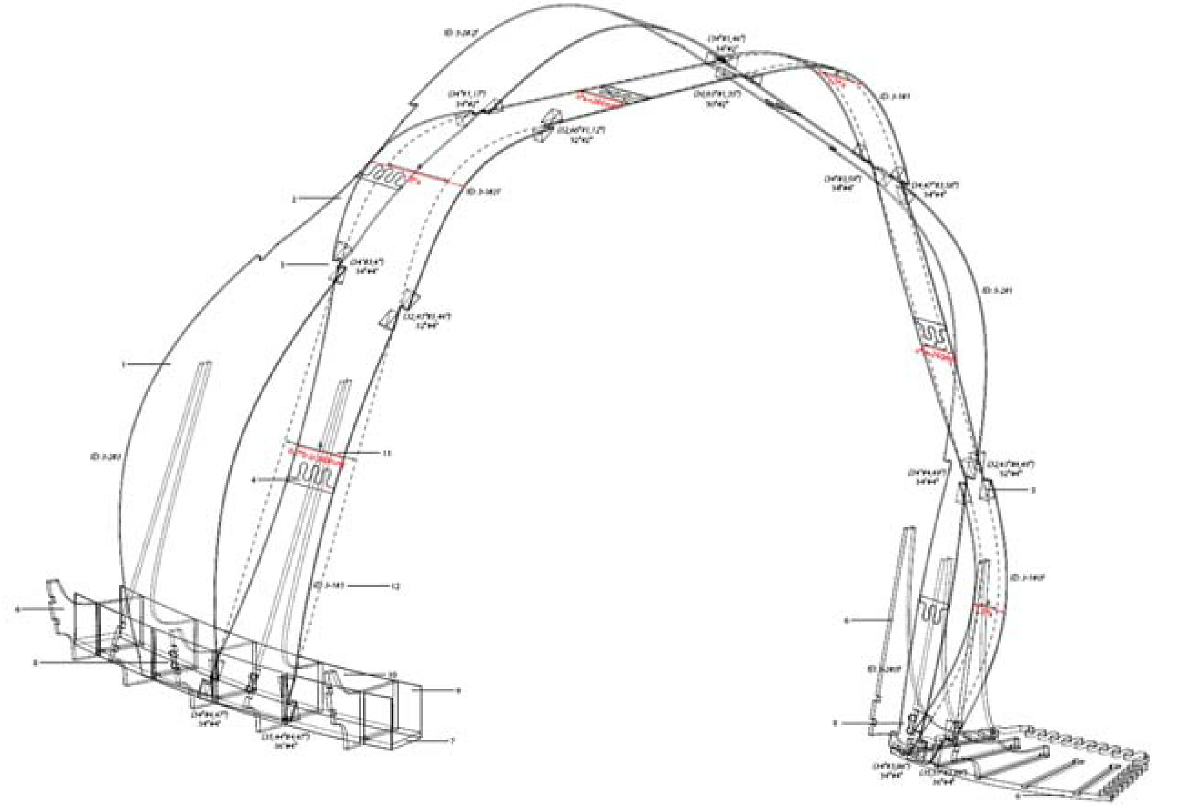
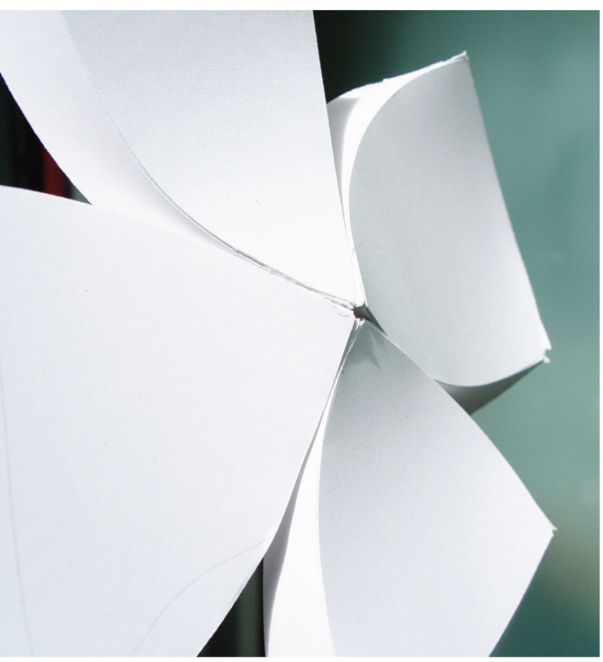


fig. 14

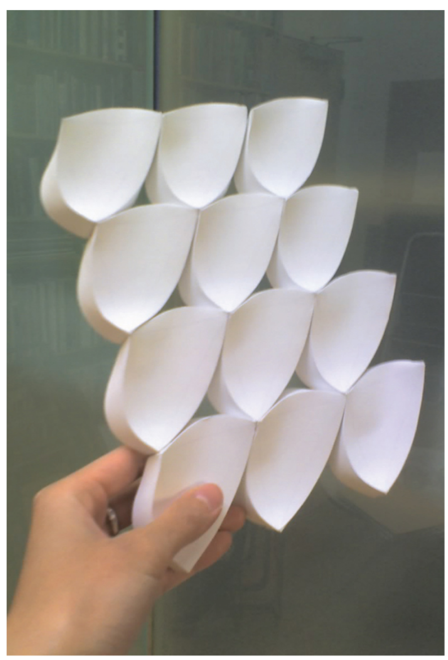
fig. 15

Annexe II

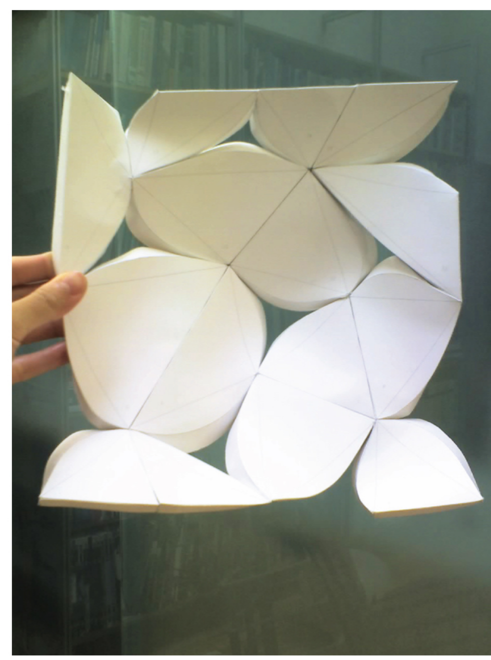
Voussoir Cloud installation



MATERIAL TEST OF JOINT CONDITION



TEST OF MODULES OVER FLAT SURFACE



TEST OF MODULES OVER CURVED SURFACE

fig. 16

LUMINOSITY TEST

FINAL MATERIAL EFFECT

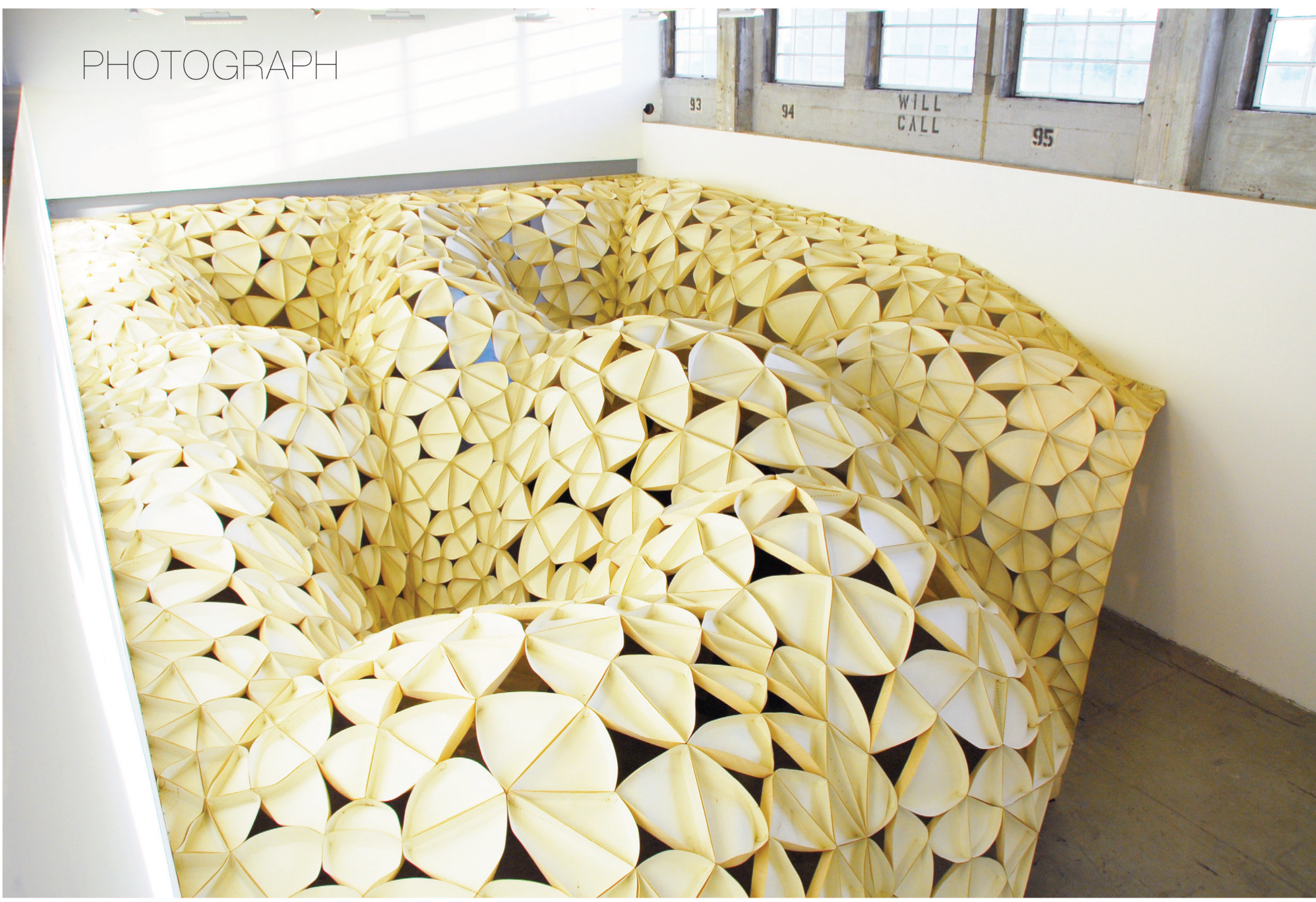
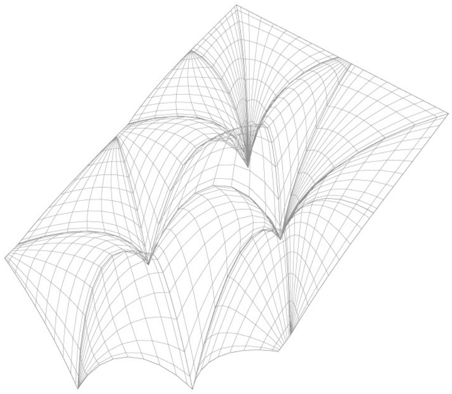
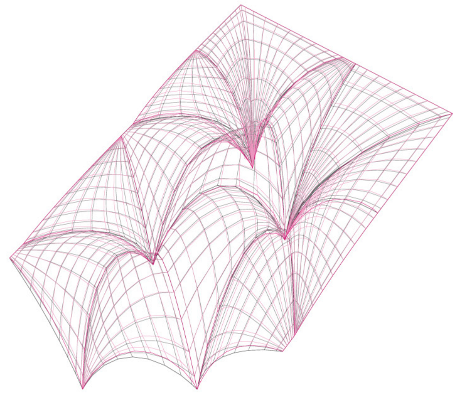


fig. 17

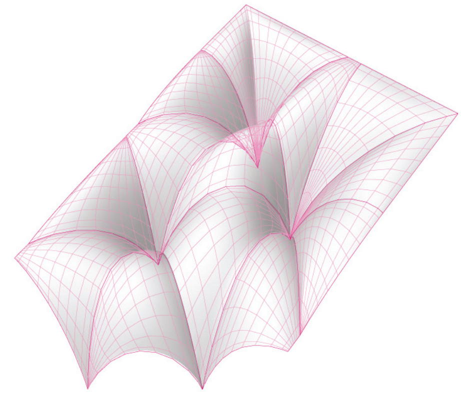
RENDERING (MAXWELL STUDIO) VS PHOTOGRAPH



ISAr INITIAL GEOMETRY



ISAr INITIAL VS. FORM-FOUND GEOMETRY



FORM-FOUND SURFACE

BACK WALL

NOTE VIEW LOOKING DOWN AT CONVEX SIDE

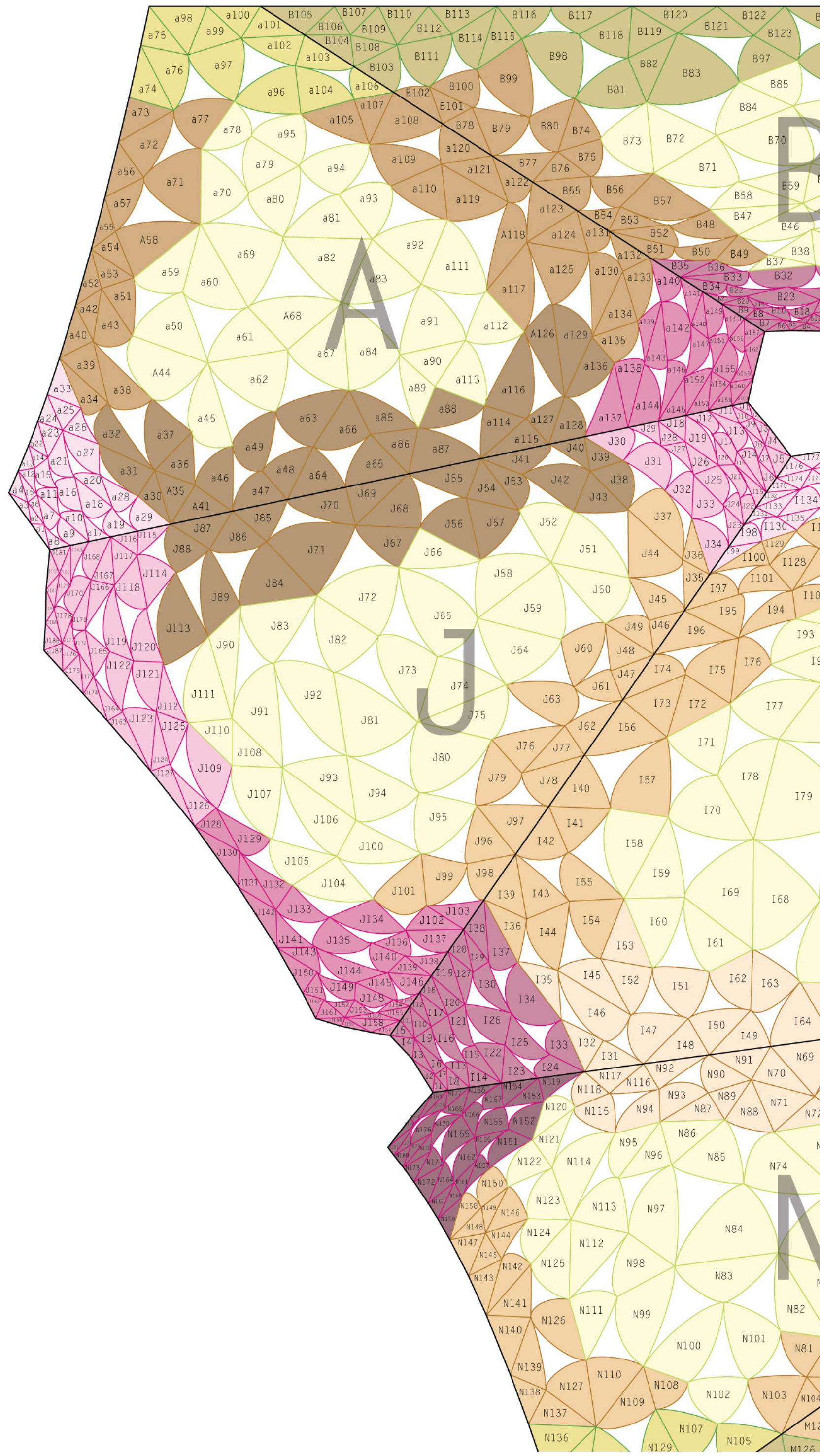
ORDER OF INSTALLATION (DIFFERENTIATION OF COLORS INDICATES DIVISION OF PARTS)

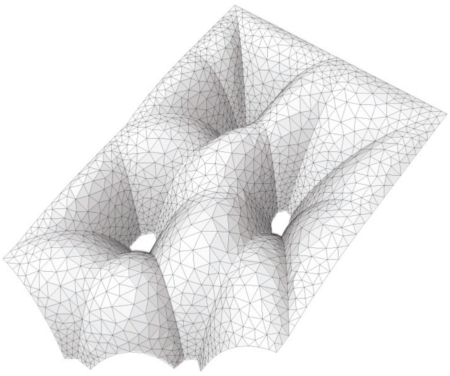
1 COLUMN FEET

2 RIBS

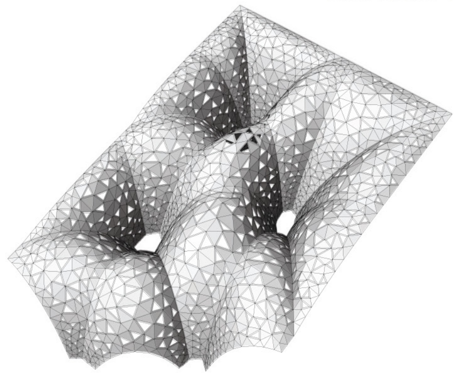
3 TOP EDGES

4 FILL LEFTOVER "HOLES"

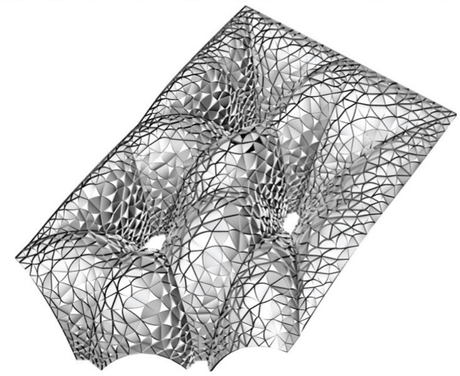




TESSELLATION OF FORM-FOUND SURFACE



POROSITY DIAGRAM



MODULE GENERATION

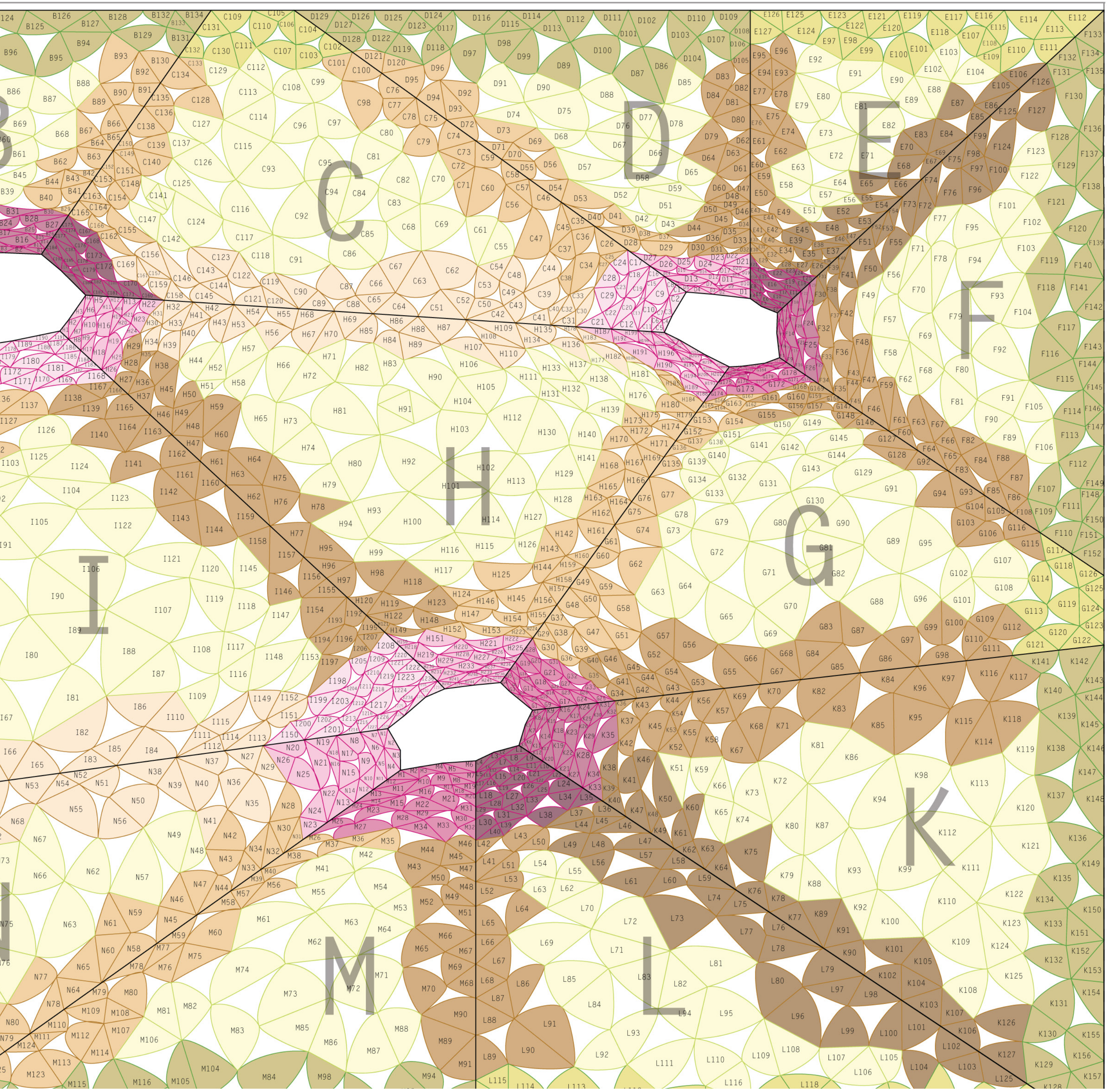


fig. 18

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