A Generative Grammar for 2D Manufacturing of 3D objects

by

Daniel Cardoso Llach
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Submitted to the Department of Architecture in Partial Fulfillment of the Requirements for the Degree of **Master of Science in Architecture Studies** at the **Massachusetts Institute of Technology**. June 2007

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Abstract

Much of the current research in Design and Computation for Architecture proposes to automate the production of construction information as a means of freeing architects from the sticky and inconvenient contingencies of dealing with physical matter. This approach has yielded promising questions and applications, but is based on two related assumptions that often go unnoticed and that I wish to confront: 1.Designers are more creative if they only need to engage with the superficial aspects of the objects they design and 2. The symbolic 3D environments of current design software are the ideal medium for design because they hide from the user the contingencies of physical matter. I examine these assumptions and the potential of a generative grammar to enable an alternative dialogue between design and construction. What happens when the generative grammar for design and construction are one and the same? In this thesis I present a generative grammar for 2-dimensional manufacturing of 3D objects as a vehicle for discussing the millenary tradition in architecture of separating design and construction knowledge.

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The Universidad de los Andes's School of Architecture and Design

My family and friends,

And Mafe for inventing all of this with me before it happened.

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Introduction

Figure 0. Steven A. Coons. An MIT Professor and early promoter of CAD/CAM.

In 1966 Stephen A. Coons, an MIT mechanical engineer and early promoter of numerically controlled machinery as creative aides, described digital fabrication devices to an audience of artists and designers as "perfect slaves" that are to perform the dirty work of dealing with materials while the designer/artist is free to "concentrate fully in the creative act". For Coons the manipulation of materials is a stage that should be hidden as an unnecessary and undesired part of the creative process. In his short lecture he ambiguously referred to the computer as a "compliant partner", as an "appropriate kind of slave" and as a "magic instrument of creative liberation" (Coons 1966). His stance towards fabrication technologies can be seen as part of a general shift in the uses of computers and other technologies in Post-War United States from military purposes to other, consumer oriented or "creative" purposes[1] .

This thesis shows how Coons's view of CAD/CAM as perfect slaves is a recent instance of a long philosophical tradition of separating the mind from the body, and design from construction. It also posits that this division, when crystallized into design tools and methodologies, tends to prevent material knowledge from participating and enriching the design process, purporting a view of design representations as clean conduits, and of construction materials as mere receptacles of ideal forms[2]. The

1 The fascination for technological advancements that emerged from the assimilation of new technologies in American society after the war has been thoroughly studied by Paul N. Edwards, who situates it in terms of the realization of an old dream of a closed and clean world of purely symbolic manipulation. For an immersion in the role of technology and computing in the construction of post-war American "closed world discourse", see (Edwards 1996)

2 The "fluidity" of forms into matter in the relationship between ideal and material forms can be traced back to Plato via Descartes. In recent works this notion is exemplified by the use of the term "externalization" in design theories like R. Oxman's Design as re-representation (Oxman 1997), where sketching is defined as the result of a transference between the mind and the paper, granting little importance to the role of the medium in the design process. This fluidity is also present in our everyday talk about design when we say or hear people say things like "I have solved the problem, I just need to draw it", or designers' usual self-deceiving statement "I have everything in my head". This "fluid metaphor" in design as

thesis proposes a generative grammar for fabrication as a vehicle to discuss this division and explore alternative dialogues between design and construction, in which materials become active participants rather than passive receptacles of architectural form.

This thesis draws extensively from my experience as a research assistant in the Digital Design and Fabrication research group at the School of Architecture and Design at the Massachusetts Institute of Technology (DDFG) to a) show how the division between design and construction is present in today's approach to digital design and fabrication, and is a persistence of a long tradition in architectural thought. And b) propose an alternative dialogue between design and construction through a generative grammar for 2-dimensional manufacturing of 3D objects.

The first section provides a background on the uses of digital fabrication machinery both in practice and in academia, focusing on the work of the DDFG, and discusses the historical origins of the division and some of its implications for architectural thought. The second section draws an hypothesis that frames the theoretical question in the terms of a generative grammar for 2D manufacturing of 3D objects; some relevant precedents are reviewed. The third section will describe the generative grammar in detail, and the fourth will show how it deals with three aspects of the material a) tolerances b) friction and c) structural behavior. The fifth section shows the grammar in action in the light of two aspects: its growth as a generative design production device and the flexibility of an object derived with it implemented in a parametric model. A final section will offer some conclusions and discussion points around the idea of transparency in computational design tools, and its implications in the always unstable professional role of the architect.

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proposed here borrows from the more general concept of conduit metaphor formulated by (Reddy 1979).

1. Background

1.1 Roles played by digital fabrication in today's architectural practice

1.1.1 Gehry & Partners and KPF: two uses of digital fabrication in today's design industry

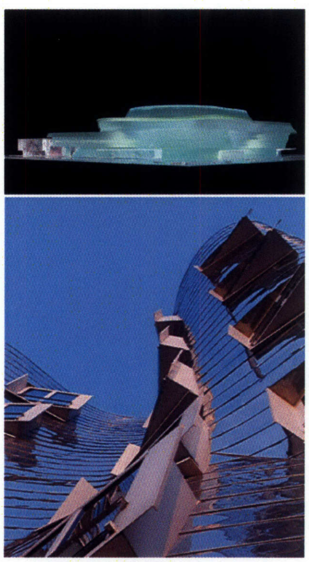


Figure 1. Two distinct uses of digital fabrication: Gehry & Partners and KPF (http://wirxli-flimflam.blogspot.com/2006_11_01_archive.html and kpf.com)

Two different approaches to the use of digital fabrication are visible in industry, they are generally separate and mutually exclusive. On the one hand a growing number of technologically advanced firms like Gehry & Partners are incorporating digital fabrication techniques in the execution of their projects, showing them as powerful aides in the manufacturing process of components of the buildings they design[3]. On the other hand, besides their use in full-scale construction, other firms such as KPF (Kohn Pendersen Fox) in London also use large digitally fabricated physical models for in-house design evaluation and as a representation aide in client briefs.

In the first case (Gehry & Partners) digital fabrication devices improve the cost-efficiency of manufacturing processes that would be difficult and labor-intensive by other means; on the second (KPF), digital fabrication is also one of many representation media that play a role on the designers team process, and as a way to communicate aspects of the project to other parties involved, a role traditionally played by architectural models. In this case it can be argued that the digitally fabricated physical models differ in degree but not in nature from physical models made with other tools.

3 In Rule-building (Loukissas 2003:22), Gehry & Partners process of design is shown as a dynamic dialogue from physical to digital, in which hand-made physical models are captured as digital models to be then handed to a group of "technologists" in the office to "try to develop rules of constructability which can be 'fit over the design intent'". The split between design and technical tasks is clear, but it is also pointed that there is a "considerable amount of feedback which propels the cycle to continue and develop". From this description I assess that the role of digital fabrication in Gehry's practice is preeminently at the construction stage, as a tool for making 1 to 1 functional mockups of the building, and specially for making it financially feasible to make a very large number of non-standardized components.

For a detailed description and classification of Digital Fabrication Machinery see (Seely 2004).

1.1.2 The work of the DDFG

1.1.2.1 Research Premises

The Digital Design and Fabrication Group (DDFG) at MIT investigates the potential overlap of both approaches experimenting mainly with single-material assembly designs. The notion of single-material systems for digital fabrication has been a topic of exploration within the group for years (Sass 2005, Botha 2005, Kashiap 2001, Griffith 2005), and draws on the assumption that in the not-so-distant future digital fabrication devices will be cheaper and more accessible, having effects on the building industry of developed countries and enabling communities to engage in cheaper and quicker design to construction processes. This overarching assumption is related to the Fab Lab initiative from the Center for Bits and Atoms[4], and is embraced by the digital design and fabrication group as part of the research premise.

Figure 2. A Fab Lab (from www.media.mit.edu/ physics/demos/)

The guiding logic of single-material design explorations in the group's work is to embed the assembly in the elements rather than relying on smaller components for joining them together[5]. This is generally solved by creating notches and slots to create a friction-based system of assemblies comparable to a LEGO kit, or a 3D puzzle. By relying on friction joints only, and by embedding these joints in the geometry of the architectural elements, other materials like glue or nails become unnecessary, and therefore the number of construction steps is reduced, together with the complexity of the fabrication and assembly processes. Other important effect of this embedment is the ability to encode a relatively comprehensive description of both design and construction information in a single digital file readable by a single machine, rather than having to create separate descriptions for different fabricators or contractors (Sass and Oxman 2006).

In the light of these premises, professionals that want to take full advantage of design technologies will be prompted to use their tools in new ways that take advantage of both fabrication devices and computer-assisted design methods.

The DDFG investigates the potential overlap of digitally fabricated designs as both design representations and as vehicles to the solution of full-scale design problems. This attempt raises questions about the

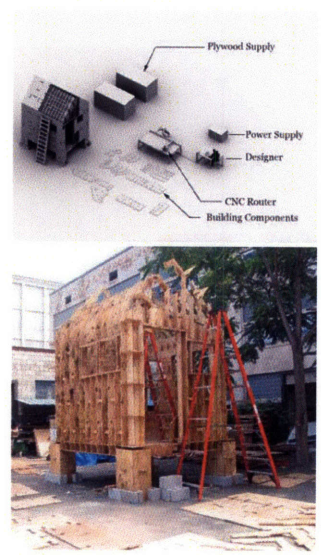


Figure 3. The Instant House Project

4 The Center for Bits and Atoms is an interdisciplinary research think-tank at the Massachusetts Institute of Technology's Media Lab. The Fab Lab initiative consists of placing digital fabrication tools and knowledge in the hands of members of third world communities. See (Gershenfeld 2005)

5 See (Sass 2005)

definition of the range within which these architectural descriptions can be used for physical and not only for visual evaluation; this definition involves not only an understanding of the machine and the design software tool, but also of the physical properties provided by the material.

1.1.2.2 The design/construction split in the DDFG

Coons's stance towards computers in relationship with creativity (see Introduction) is present in part of the DDFG talk about digital design. In one of the sessions of the research workshop on digital design and fabrication conducted at MIT, one of the staff members put forward a view of the role of computers and machinery in design creativity in strikingly similar terms to Coons's:

The visual, the surface, is most of what architectural training is about; that's what the architects are really good at (...) the other part [the "physical Layer"] is in the back, and that's what we really want to automate, and that's what most of computing is about. This is how the system becomes a scaffold for truly creative work.

The concept of creativity in this proposition stops at the visual, which is implicitly linked to the "soft" and "human". The role of construction, in contrast, falls outside the sphere of the creative, and is linked to the "hard" and automatable. Its role as a "scaffold" for creativity renders it passive rather than active participant in the generation of designs. Computation is to protect the designer of these contingencies, and in the process materials become mere receptacles of ideal forms. As in Coons' scenario, the physical is to be hidden and out of the sight of the designer, in the hands of the digital slave.

Particularly worthy of discussion in this model is the opposition between a "visual layer" to which "design" and "creative work" are confined and a "physical layer" that is the domain of computers and machinery. In this distinction the visual is associated to the intuitive, the imaginative and the creative, and the physical to the objective, functional and "technical". Turkle's description of the differences between "hard" and "soft" mastery offers a concise illustration of this distinction:

Hard mastery is the mastery of the planner, the engineer, soft mastery is the mastery of the artist: try this, wait for a response, try something else, let the overall shape emerge from an interaction with the medium. It is more like a conversation than a monologue

The work of the DDFG is founded on the premise of this distinction, in which the visual is associated to the imaginative and soft and the physical to the technical and hard. Concerned solely with the mechanism of translation of the "imagined designs" to the construction information, the research projects of the group place computation in a sort of middle ground between design and construction, to which the medium and logic of designs are irrelevant. Design media are supposed to reflect seamlessly the "creative idea", and are portrayed as a generic and non-descript 3d modeling environment where formal operations take place to give a mental design its final shape, a clean conduit for the externalization of mental designs[6].

Echoing Turkle's talk on computers as mirrors of the mind, the modeling environments of design software become "objects to think with", windows through which we frame concepts like creativity and design (Turkle 2005). In this particular case, this framing crystallizes a notion of creativity as a process that takes place in a supposedly clean and mental visual field of formal manipulation, where the contingencies of materials are rendered invisible in favor of a general and supposedly fluid non-material design substance.

This fluidity, with its seemingly direct connection to the mental world of design ideas, is problematic, as it disregards the intentional nature and inherent biases of design software as cultural objects[7]. In this portrait of a creative design-construction process, not only the materials are hidden or deleted; the medium, the interfaces, are also rendered invisible as neutral or unimportant actors in the process of generation of form. The designer is a *bricoleur sans materiale* (his materials are invisible).

1.1.2.3 (Design in the age of) Mass Customization

Customized Digital Manufacturing (Botha 2005) is a project that illustrates the deletion of materials and design media in creativity; in this work the designer is portrayed as the end-user of a tool that hides the process that transforms a "fluid" shape into a set of components for assembly. In this procedure, the proposed tool allows the designer to focus "on proportion, aesthetics and personalization, while the more complex processes work seamlessly in the background".

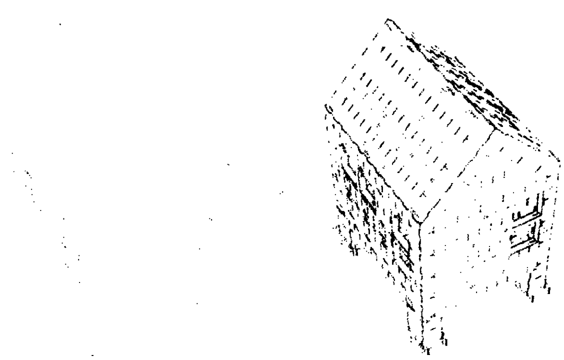


Figure 4. Design to construction

6 For an example of the use of "externalization" in this sense, see (Oxman 1997)

7 (Mitchell 2000)

The kind of tool depicted here has the objective of allowing people without technical skills to "design"; design is understood in this context as a superficial engagement with the surface of architecture, a fluid manipulation of symbolic representations of non-physical forms. Through this separation the designer is supposed to "incorporate human emotion and vernacular expectation" into the building and to "alleviate community apprehension through allowing them to take ownership of the process". An inherently restrictive flexibility is offered as complete, and in this process the meanings of creativity and design are transformed, becoming digitized features of a marketing model often described as mass-customization. Within this model the split between design and construction is a useful device that enables its promoters to market a product enhanced by its flexibility. The de-skilling of the designer is in the light of this interest a required condition, and therefore its implementation through technology becomes a desirable research goal.

1.2 Origins of the design/construction divide

Figure 5. Frontispiece of Abraham Bosse's treatise on stereotomy. From (Evans 1995)

The dichotomy between design and construction is not, however, a consequence of the computer, not even of the industrial revolution; design technologies crystallize trends that are necessarily a part of existing architectural discourse. A series of analogies can be traced between the "adequate kind of slave" of Coons and the "scaffold for truly creative work" of the DDFG group, as modern versions of a discourse whose origins can be traced back to the "skilled craftsman" of Alberti.

In his Ten Books of Architecture, Rennaissance architect and scholar Alberti established the famous distinction between lineamenta and structura[1]. This distinction would become a powerful dialectic device for future thinking about architecture and its relation to construction . Although there is no full agreement in what Alberti precisely meant by lineamenta, his writings give clues about it being very close to the sphere of representation, concretely to the building's ground plan, where the architect should embed all his knowledge and judgment. In words of (Lang 1965) "The lineamenta derives from the mind, and the material from nature". For Alberti lineamenta means design; a domain in which "all the ideas of the architect are incorporated". In Alberti's vision the materialization of the architect's design, its structura, should be performed by a skilled craftsman: in Alberti's vision there is a clear divide between the 'organizational' sphere –the sphere of the architect's reasoning-, and a physical sphere –the sphere of the engineer- that has persisted until today. However Alberti's distinction must be read keeping in mind that at his time the modern social role of the architect did not exist, although Alberti's role as a Renaissance scholar and architect is an early precedent

1 Before Alberti, Vitruvio (I b.c.) had already expressed the distinction ratiotinato et opus (reasoning and work),

–yet distinct- of the "gentleman architect" that would appear later in England during the second half of the seventeenth century.

The roles of the master builder and of the architect would become definitely separate at a very precise moment in history. Historian of construction Jacques Heyman locates this professional split in the figure of Christopher Wren, a professor of astronomy in seventeenth century England who "had never worked on a building site" but that faced the challenge of efficiently controlling the reconstruction of many buildings in London after the great fire of 1666. Because of the scale and number of the works commissioned, Wren and partners' architectural practice was forced to deal with the construction in a way that differed from the medieval practice of the masons. Taking a step away from the sphere of material manipulation by a single master builder (by using "contractors") and taking an organizational distance from materials, new social roles, new models of authorship, and new financial management schemes in construction emerged, thus giving origin –as is argued by this author- to the modern architect, characterized by its social role of mediator between the client and the builder (Heyman 2003).

According to Heyman, rather than the traditional process of apprenticeship, Wren's knowledge of architecture had been acquired by a one year stay in Paris where he observed salient buildings and monuments, and through books (he particularly mentions a 1512 latin edition of Alberti's Ten books of Architecture). Architecture treatises would play a major role in the consolidation of the modern architect by rationalizing practices that had been the sole domain of the so far unspoken skills of craftsmen; in The Projective Cast: Architecture and its three Geometries, Robin Evans shows how XVIII century French treatises of stereotomy[2] are key examples of this process of rationalization of technique that reflected the increasing division between technical and intellectual perspectives on construction, often causing tensions between the different social groups involved. (Evans 2000)

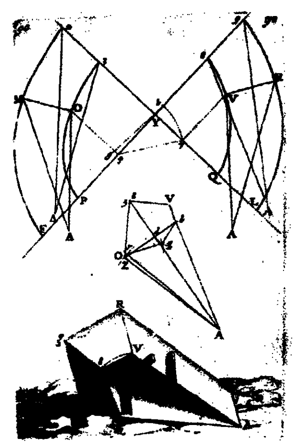


Figure 6. A block of stone and its trait, by Abraham Bosse, from (Evans 2000)

Not exclusive to architecture, the division between design and construction resonates with a more general division between the mental and the material, a dualism that is described by many authors as a defining feature of modern western thought and society. Tim Ingold has suggested that this dichotomy is so engrained in our culture that "we are inclined to use it as a window through which to view practices of all kinds, past and present, Western and non-Western, human and animal" (Ingold 2001). Other authors, like (Helmreich 1998) have noted both the platonic undertone of this division, and its resemblance to the Cartesian dualism between mind and body.

2 Hypothesis

A generative grammar for 2-dimensional manufacturing of 3D objects can serve as a vehicle for discussing alternative roles for material knowledge in a design process.

Much of the current research in Design and Computation for Architecture proposes to automate the production of construction information as a means of freeing architects from the sticky and inconvenient contingencies of dealing with physical matter. This approach has yielded promising questions and applications, but is based on two related assumptions that often go unnoticed and that I wish to confront:

1.Designers are more creative if they only need to engage with the superficial aspects of the objects they design and

2. The symbolic 3D environments of current design software are the ideal medium for design because they hide from the user the contingencies of physical matter.

I examine these assumptions and the potential of a generative grammar to enable an alternative dialogue between design and construction. What happens when the generative grammar for design and construction are one and the same?

In this thesis I present a generative grammar for 2-dimensional manufacturing of 3D objects as a vehicle for discussing the millenary tradition in architecture of separating design and construction knowledge.

I believe that the dynamic tension between abstract and material thinking is key to design, and that the organic dialogue between materiality and form is a defining feature of our aesthetic judgments on architecture.

Figure 7. GIK Assemblies (from www.media.mit.edu/ physics/ demos/)

2.1 Precedents

2.1.1 GIK assemblies (N. Gershenfeld)

GIK, first developed at the Media Lab by Neil and Grace Gershenfeld, stands for "Great Invention Kit", and is a system of 3-dimensional assembly that is composed of a single elemental type, also called GIK. These elements are assembled by friction and can be produced at any scale and in different materials (Popescu N.d. [1]). The assembly methods vary according to the scale, and at very small scales can be "printed" following the logic of an ink-jet printer. The shape of the GIK is such that small errors in assembly can be corrected, facilitating the assembly at micro-scales (Popescu N.d. [2]). It has been suggested that large scale GIK s can be used to assemble buildings.

Although the GIK assemblies show both the flexibility afforded by having a reduced design vocabulary, it also serves as an example of its the limitations when it comes to create architecture. Its relative "isotropy" makes the GIK a promising 3D printing method of prototypes or micro-scale artifacts, but it is not yet clear how it would serve to create enclosed spaces, a requisite of almost any building.

2.1.2 Parametric 3D modeling for construction (Rafael Sacks)

This is an example of a computational design tool that takes into account the properties of the materials, in what we might call "structurally conscious parametric design". It shows the benefits in terms of productivity, reduction of errors that result of the disparity between different design descriptions, and functionality of using parametric modeling for the design of precast concrete (Sacks 2003).

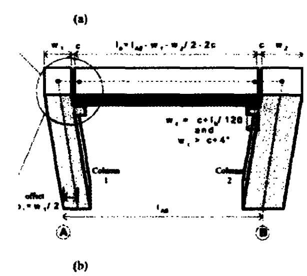


Figure 8. Sacks and Eastman: Parametric pre-cast concrete (Sacks 2003)

This project is full of interesting insights into how to implement structural knowledge in a CAD driven design process, however the results are still 2-dimensional descriptions of objects, rather than the objects themselves, or the information for the computer-controlled manufacturing.

2.1.3 Why can't CAD be more like Lego? (Mark Gross)

The paper describes CKB (Construction Kit Builder), a computational design environment based on defining, then working within, a system of components and rules for their placement. In construction details, the components and placement rules are standard; in less routine design tasks they are not. CKB uses a constraint-based, object oriented, system architecture to provide two levels of design support. At the higher level, designers of technical systems use CKB to specify components and rules for their positioning. At the lower level, building designers use CKB to lay out components of these systems. (Gross 1996).

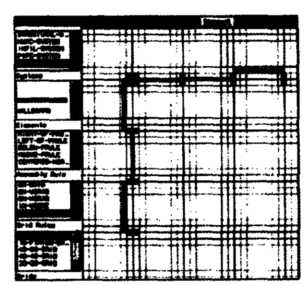


Figure 9. CKB Interface

As a design tool CKB is based on defining, then working with, a system of components and rules for their placement. At a high level, CKB allows a designer of systems to input components and rules for their positioning. At a lower level, a user (a building designer) uses CKB to lay out components of these systems.

The design components are symbolic representations of architectural objects with no clear connection with manufacturing methods. The results of the are therefore graphic descriptions of objects, rather than the objects or the information ready for their fabrication. There is no negotiation either between the growth and the flexibility of the designs.

2.2 Methods

2.2.1 Digital Fabrication

Figure 10. Lasercutter

The different prototypes presented in this document are derivations of the generative grammar. As an extension of the Wood Frame Grammar (see Background), the fabrication of these prototypes was constrained to 2D cutting techniques which can include water-jet cutting, plasma cutting, CNC cutting, and laser-cutting[3]. All the prototypes in this thesis were fabricated using a Universal Laser Systems - X-660 laser cutter (50 watt), which employs a laser of adjustable power and speed to cut planar sheet materials. This machine is capable of cutting sheets with a maximum size of 32x17 in, and of variable thickness depending on the material employed; the machine is typically used to cut materials such as chipboard, plywood, balsa wood, masonite, acrylic, and plexiglas.

A defining characteristic of this machine is that it is "two-axis", which means that the arm that carries the cutting device (the laser) can only move in the X and Y axis. This condition constrains the laser cutter to make cuts exactly orthogonal to the sheet of material, deeming impossible any beveling or embossing on the materials. Machines of 3, 4 and 5 axis are available in the market at greater expense. The machine is physically connected to a computer equipped with a CAD software (AutoCAD2004), from where the instructions are sent to the laser cutter to perform the cuts as specified in a loaded drawing file. The process is similar to printing a document in an inkjet printer.

When cutting, the laser beam burns part of the material, and this needs to be considered in the preparation of the file; the amount of material that gets burned by the laser depends on the type of material, and on the power and speed of the head.

2.2.2 CAD systems

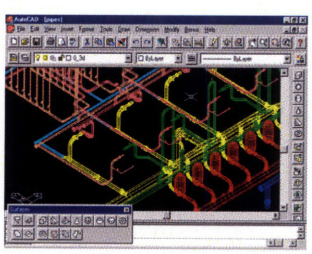


Figure 11. AutoCAD Interface

There are several computer aided design systems today in the market. For the purposes of this document I will separate them into two categories, even though the line that divides them is not always completely sharp.

2.2.2.1 Solid Modeling and Drafting Systems

3 For a detailed descriptions of different digital fabrication machines refer to (Keely 2004).

I will call the first category "solid modeling and drafting packages", and it is exemplified by software like AutoCAD and MicroStation. These packages are often regarded as "traditional" CAD systems because they are to a large extent an automated version of the traditional drafting table of the architect or engineer. The notion of computer aided design as an automatization of hand drawing and drafting methods was the leading metaphor in the early development of these tools, which evolved from the practical necessity of managing large amounts of information on designs in a faster and more efficient way than paper allows[4].

Hence the computer screen was transformed into a window looking to the surface of a virtual drafting table, where traditional drafting tools could be simulated and automated by means of the graphic user interface, which would provide a set of virtual versions of traditional drafting tools like rulers, pens, T-Squares, scissors, glue and drafting paper, conveniently arranged inside "toolboxes". AutoCAD was born from this frameset, and even though it has evolved into a relatively flexible and versatile drafting package for 2D and 3D representation, it preserves traces of its origins as an automated drafting table; in contrast with parametric modeling packages (the second category, described in the next section), solid modeling and drafting packages are primarily non-hierarchical and non-relational. This favors a type of design moves based on design transformations and operations such as copy, array, mirror, rotate, etc., and prevents almost completely the relational propagation of changes. The solid modeling and drafting package used for the early experiments is AutoCAD 2004 by AutoDesk.

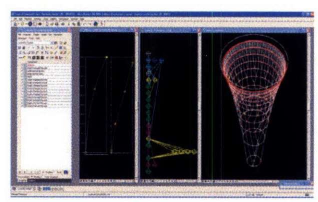


Figure 12. Generative Components Graphic User Interface

2.2.2.2 Parametric Modeling

The second category of design systems is parametric modeling systems, also can be described as relational modeling systems; these allow users to define geometrical entities by establishing relationships of geometrical or mathematical dependency between different parts of the design. Two examples of design systems often referred to as parametric modeling systems are CATIA, developed by Dassault Systemes for the airplane industry[5], and Generative Components, developed by Robert Aish at

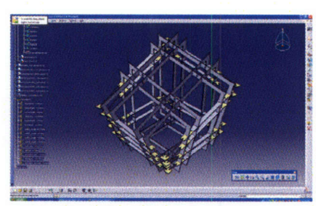


Figure 13. CATIA V17 Interface

4 Ivan Sutherland's Ph.D. thesis at the Massachusetts Institute of Technology, the Sketchpad, is the ancestor of modern CAD systems (Sutherland 1963), consisted of a screen where the user could draw on using an optical pen. From that point on, and until very recently, the evolution of the interaction between the user and the machine as CAD systems developed can be described as a constant strive to mimic the interaction between the designer and his/her physical drafting table and drawing tools. Interestingly the first CAD systems were implemented by the car industry in the sixties, and only decades later by the architectural industry.

5 CATIA was later adapted to aid in the architectural practice Gehry and Partners through a partnership between Dassault Systemes and what later became Gehry Technologies headed by Dennis Shelden. The new software, to a large extent a subset of CATIA, was called Digital Project.

Bentley as a parametric plug-in for the more "traditional" solid modeling and drafting package Micro Station. I will describe parametric modeling in a way that is general to both systems.

If using a solid modeling and drafting system feels like drawing 2D objects in a drafting table, using a parametric model feels like putting together a machine in a table full of springs, gears and rulers; in this "inventor's table" fluid materials and tools are available for the designer to build geometric "mechanisms" rather than static representations. In a parametric model there is generally a distinction between a driving geometry, generally a small set of geometric elements and parameters that govern the behavior of the model through chains of dependency, and a driven geometry, that is given by a potentially large set of geometric elements and parameters at the bottom of these chains of dependency, changing in accordance to the dictates of the driving geometry, inside the constraints defined in the model.

This constraint based modeling process explains why parametric models are, in contrast with models built with a solid modeling and drafting package, extremely hierarchical, and therefore favor a top to bottom design manipulation through propagation of constraints over a bottom to top design manipulation through the addition and subtraction of elements.

The power of a good parametric model is that once the constraints and chains of dependency are defined by the designer, the driving geometry can be changed in order to produce design variations. In contrast with solid modeling and drafting packages, parametric models define a "solution space" rather than a static description of an object. To the eyes of many professionals, the flexibility afforded by parametric modeling makes this systems "the future of architecture"[6] and these tools are already part of the curricula in many architecture schools including MIT's. This is notable since only very few firms in the world actually use parametric modeling packages due to their high prices and to the very high level of competency required from both the designer and the fabricator: only expensive specialists can take full advantage of them. (Wodzicki 2003).

In terms of the kind of interaction that these systems promote with their users, it is important to note that the artifacts created in them are meant to be "operated"; this apparently simple idea points to a major change in the division of the disciplinary roles of the designer: parametric machines need operators, users, and even though usually the creator can be the user as well, this doesn't necessarily have to be the case.

6 The expression was used by Peter Eisenmann in a Spring 2007 lecture at the Massachusetts Institute of Technology. In his keynote speech in SIGRADI in November 2006, John Frazer also describes parametric modeling packages (specifically CATIA) as "the single most advanced piece of design software in the market today".

The parametric modeling system I used for exploring the possibilities of the grammar was the student version of CATIA V17 by Dassault Systemes.

2.2.3 Observation

As a research assistant in the Digital design and fabrication group, my work has dealt with the incorporation of fabrication devices in the design process in a variety of settings. Being an instructor and part of the research staff in the workshop Special Problems in Digital Fabrication has afforded me a privileged position as both a participant and an observer of the course, which focuses on the investigation of desktop scale rapid prototyping as a means to adequately solve, represent and/or simulate conditions and problems present in full scale buildings, specifically façade solutions for high-rise towers. As part of the staff I have attempted to communicate my own experiences and findings with the machines and prototypes, with the hope of fostering a quicker learning curve in the participants, and a reflective discussion on our use of these tools. Another instance of observation was my participation in the summer 2006 research session of the Digital Design and Fabrication group, in which I started developing the physical prototypes that I present in the next sections of this thesis. In this context I worked together with other researchers that dealt with similar problems but in different material/device scenarios.

Most of these observations were taken in the form of ethnographic field notes that will be presented in the Discussions chapter. I will use quotes and descriptions of the situations in which they took place, all of which emerge from meetings of the research workshop and interviews with students and faculty; in all cases the names are changed or not mentioned at all in order to preserve the confidentiality.

Figure 14. General components of a closed volume

3 The grammar

3.1 Going pre-rational[7]

An new subdivision strategy is devised that is not derived from structural concerns, but from a morphological subdivision of the box in corners, walls and end-walls. A grammar composed of these elements can be used intuitively to compose spaces, like a LEGO kit.

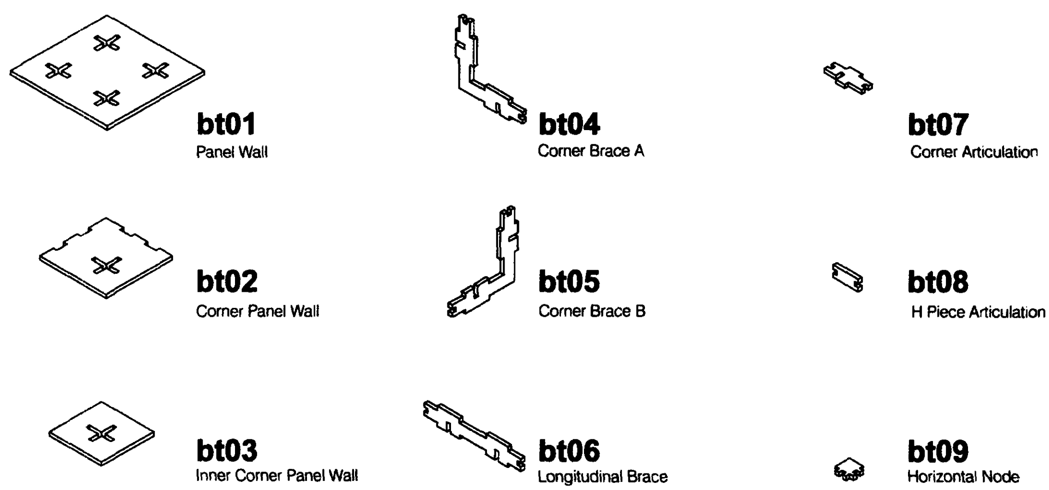


Figure 15. Basic Types

It is important to note that the subdivision strategy carries a great deal of design implications, and is a design decision in itself. Other subdivision strategies will result in a different "universe" of designs that can be

7 Pre-rational makes reference to a certain approach to design in which the components for the construction are defined beforehand. In contrast, in a post-rational process a global shape is approximated by geometric strategies to infer the set of components needed for its construction. For a discussion on the origins and meanings of these two terms see (Loukissas 2003).

generated by using the grammar rules (Figure). Some interesting alternatives were explored by the participants of the Special Problems in Digital Fabrication Workshop at the Massachusetts Institute of Technology in the Spring of 2007.

The elements of the vocabulary were defined to respond flexibly to each one these conditions. The following sections describe different aspects of the grammar for the design language.

3.1.1 Vocabulary

The vocabulary of the grammar is composed of a set of three compound types, which in turn are composed of a total of 9 different basic types. The sequences of assembly are studied so that there is only one assembly vector in each assembly move. These sequences of assembly are meant to be deterministic derivations of grammar rules[8]. The composition of a design with this set of building blocks is, however, non deterministic, as will become clear in following sections.

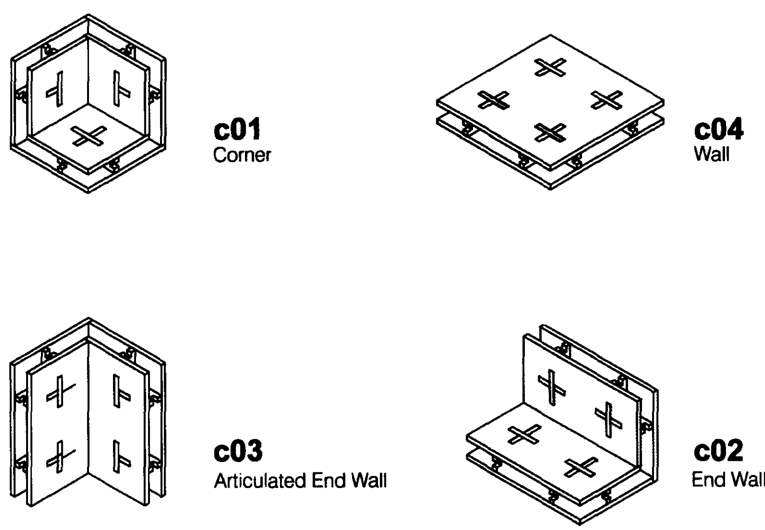


Figure 16. Compound Types

The elements of the vocabulary are defined geometrically in the model with the tools provided by the software; the geometric definition of these objects is stored. Computer Aided Design software uses file formats like DXF[9] for storing the information from each design entity in a database.

8 See (Knight 2000) for a detailed distinction between deterministic and non-deterministic grammars.

9 Drawing Exchange Format

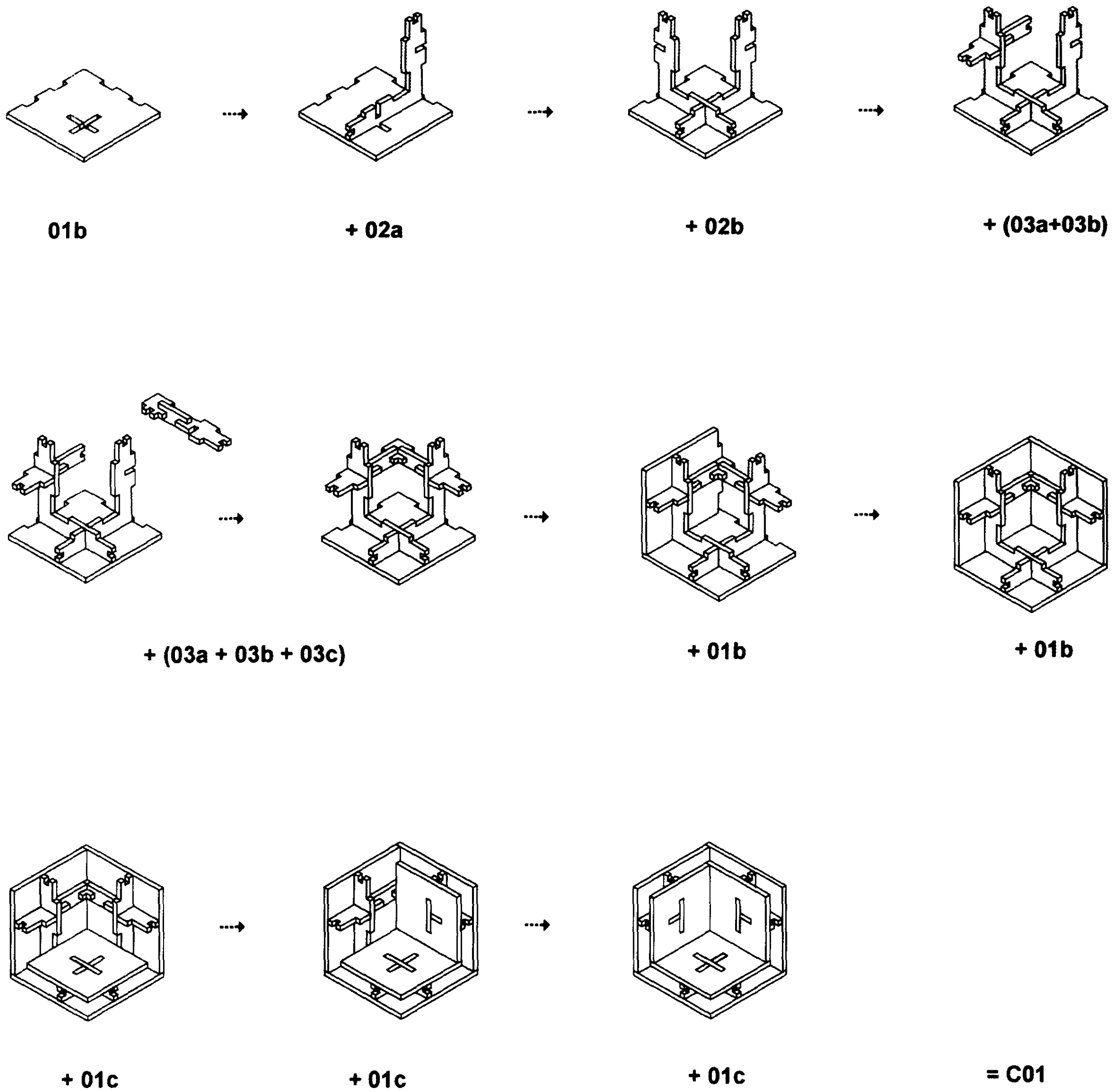


Figure 17. Deterministic derivation of corner

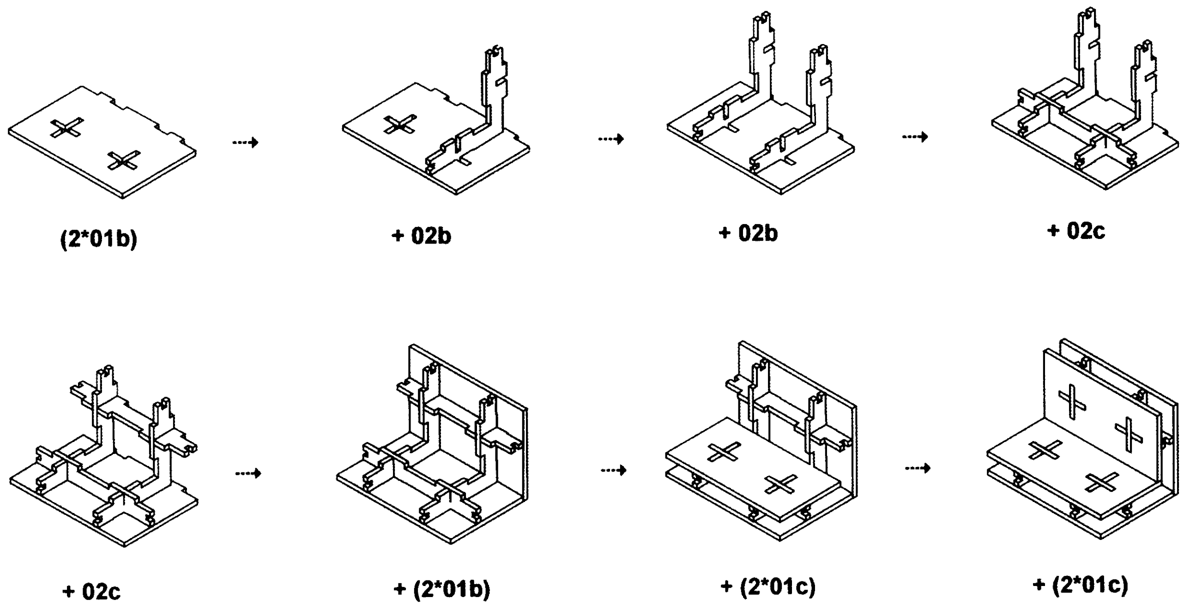
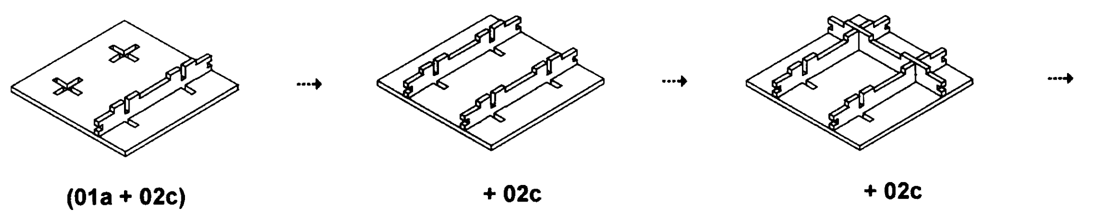


Figure 18. Deterministic derivation of end wall



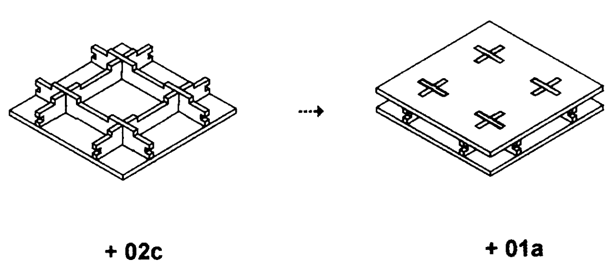
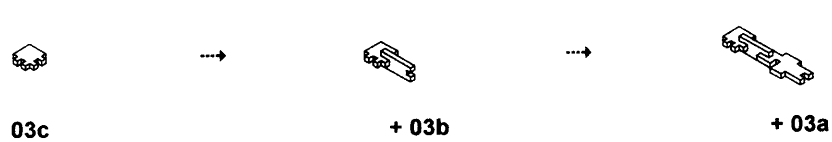


Figure 19. Deterministic derivation of wall panel and articulator



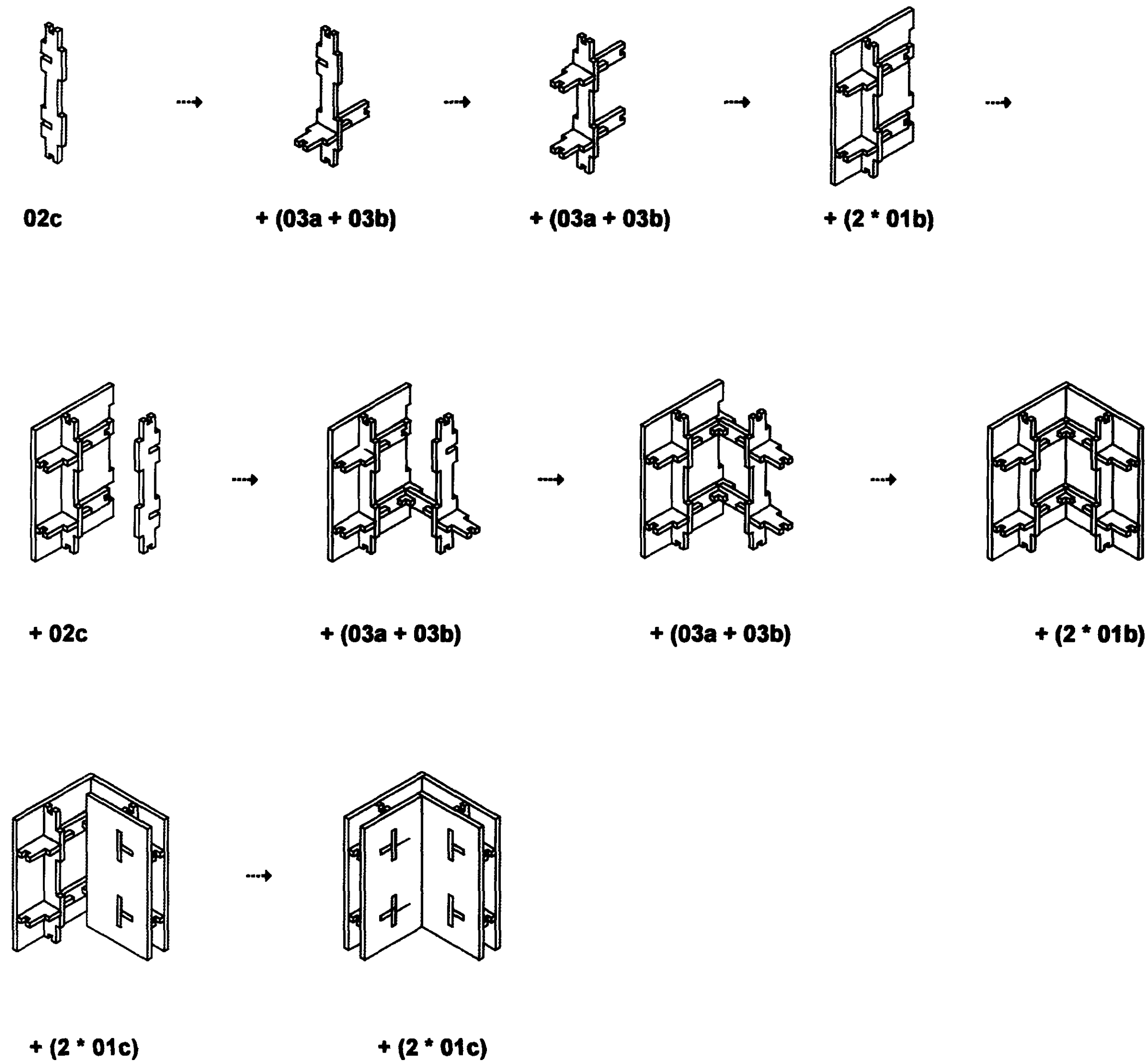
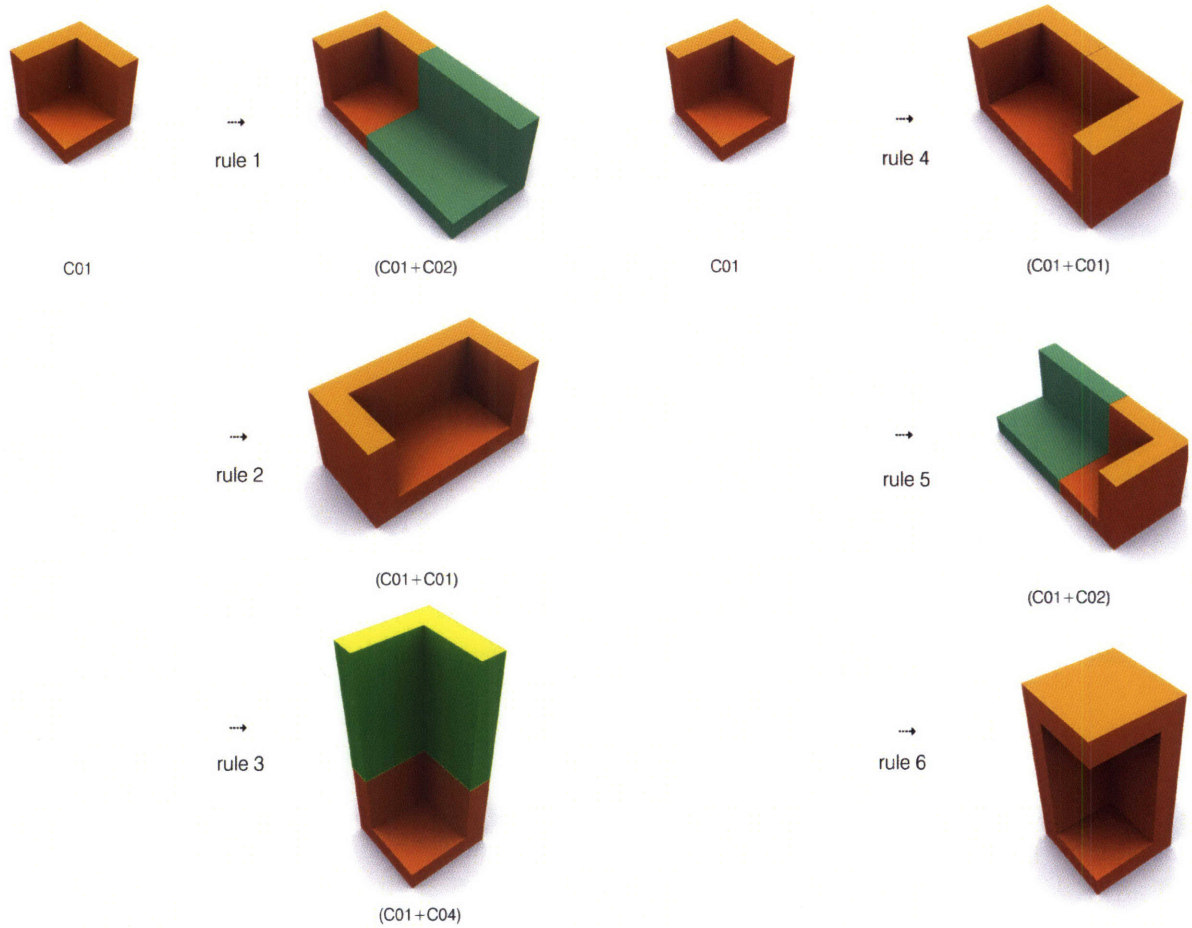


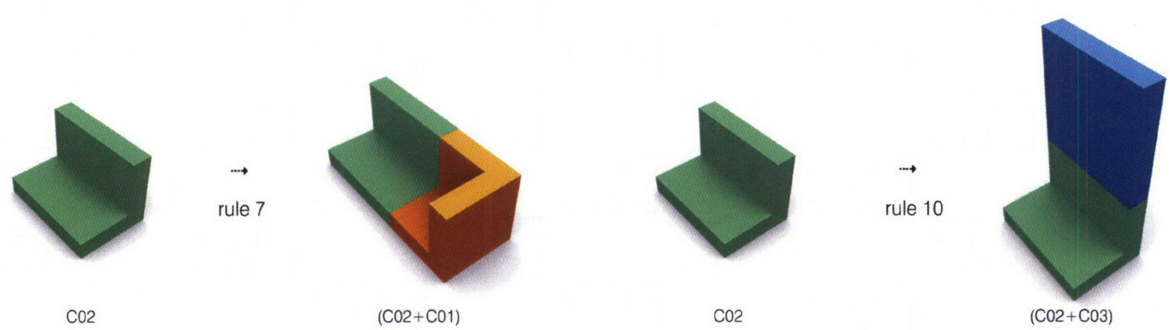
Figure 20. Derivation of articulated end-wall

3.1.2 Rules of Transformation

The application of the transformation rules on the elements of the grammar is non-deterministic, and therefore can produce an infinite number of designs. Rules of transformation provide the framework for generative design.In the following pages I will show these rules.

The manipulation of the transformation rules yield a potentially infinite number of designs through operations of addition and subtraction of elements. Furthermore, the relationships of dependency between different values in the grammar define the way the propagation of parameter variation takes place, providing the framework for affording variation of the global shape. This will be evidenced through a relational model built in CATIA and described in a later section.





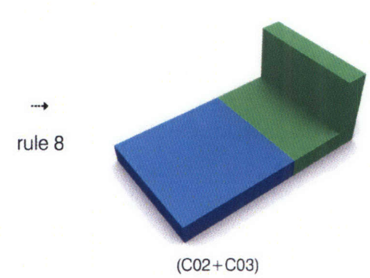


Figure 21. Examples of transformation rules for the corner component

Figure 22. Examples of transformation rules for the end wall component

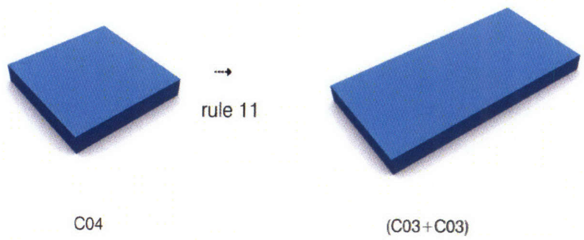


Figure 23. Examples of transformation rules for the panel component

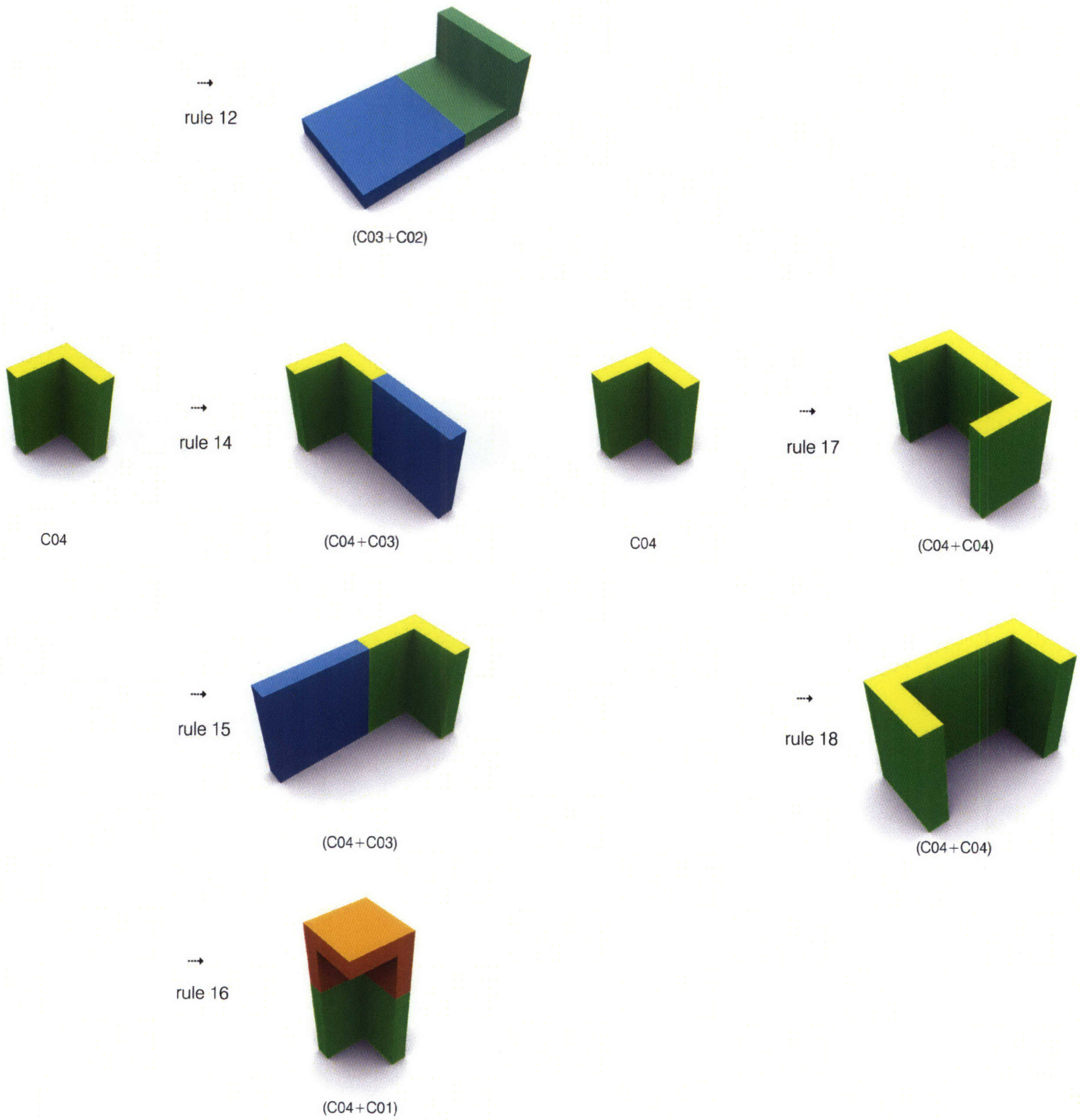


Figure 24. Examples of transformation rules for the articulated end wall component

3.2 The material digitized

In this section the role played by material knowledge in the grammar is explained. Computer Aided Design software uses file formats like DXF for storing the information for each design entity in a database. Design entities such as lines, points, curves and surfaces have specific data structures that allow the geometry to be constructed and reconstructed mathematically in the modeling environment. In order to make the elements of the vocabulary flexible to global changes, these data must be defined in a general way, such as in terms of relationships of proportions between different data fields, or as a function of a global parameter that provides the element with information about the specific nature of relevant material and structural issues, or about the particular fabrication method.

The generality of the description will afford the versatility of the system to operate at different scales and materials (for example 1/32" chipboard, 1/8" Plexiglas, or 1 inch plywood). The parameters taken into account in the grammar are a) Tolerance b) Thickness of material c) Size of the slot d) Distance between slot and end of the piece e) Depth of the slot f) Distance between slots.

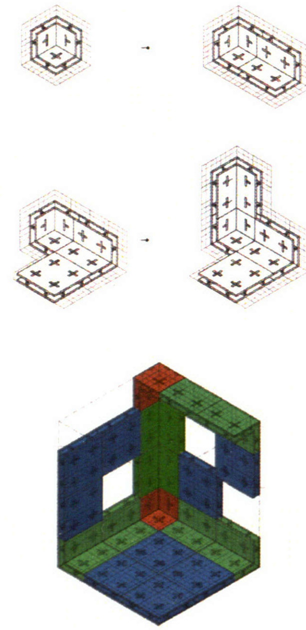


Figure 25. Design derivation using addition rules

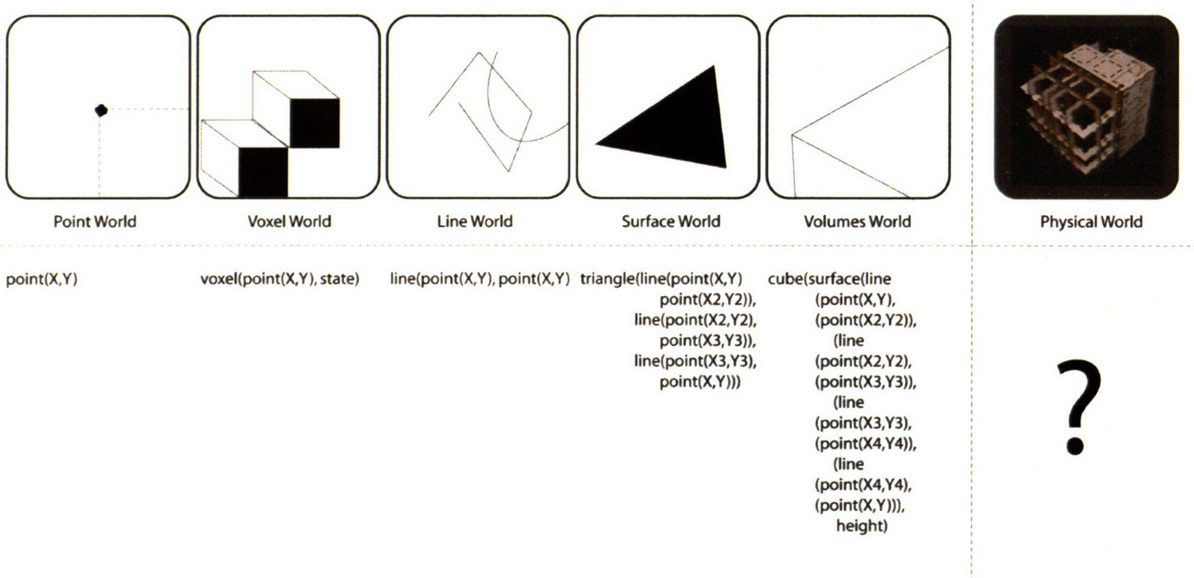


Figure 26. Computational representations of design worlds. Inspired by (Mitchell 1995)

3.2.1 Dealing with friction

A key component of the grammar is de H-joint. In order to find an adequate dimension a series of test was conducted on several instances of the joint in different sizes. The objective was to study the relationship between the length of the connection piece (and therefore the friction area of the joint), and the strength of the connection. This study took into account vertical loads only. It was done using the Instron machine at the

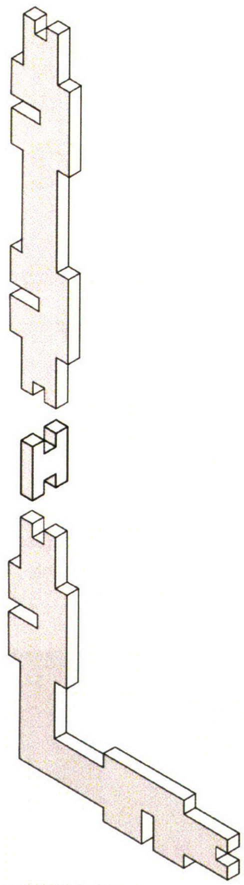


Figure 27. H-Joint

MediaLab. This machine measures accurately the strength required to pull apart the joints. The goal is to find a joint size that a) provides is not loose but still b) can be assembled manually.

The Coulomb experiment yielded the friction coefficient of plywood. The experiment consists in finding the angle at which a surface is when an object on it starts sliding.

Although the friction force is not a function of the area, it is a function of the weight understood as normal force. u = angle, which in the model is determined by the pressure exerted by the braces caused by the tolerance of the joint.

The measurements and experiments resulted in an adequate value of 1/8 in for the H-joint piece, and a tolerance of 0.01 in.

For the load measurements, we chose a constant value for h (0.25 in), and a variable d, in 1/8 in, 1/16 in, 1/4 in and 3/4 in sizes.

As a result of these measurements and inquiries I was able to determine that a) H-Joints over 1/8 in behave almost the same, and b) Confirm that the strength of the joints is to be determined by the tolerance, and not by the area.

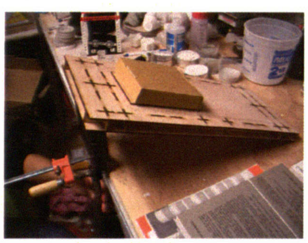


Figure 28. Coulomb experiment (Friction coefficient of plywood = 0.37)

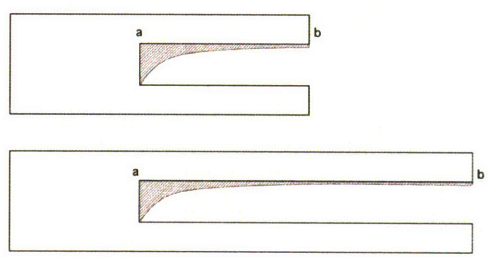


Figure 30. Diagrams of the measured pieces

3.2.2 Dealing with tolerances and non-perpendicularities

The correct tolerance value needs to be assigned to the joints, as this is the critical value that will provide rigidity to the assemblies. The tolerance value should be such that it a) provides firmness and b) can be assembled manually.

The assessment of the tolerance is to a large extent a result of a trial and error process. As a result of the trial and error process, and of the geometrical solution of the angled slot problem, I was able to determine that the right tolerance for the plywood I was using was 0.254 mm (0.01“).

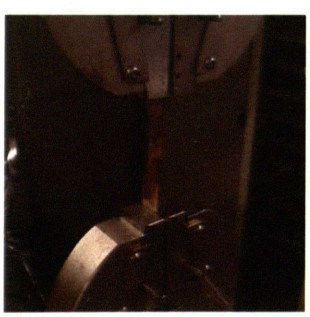


Figure 29. Instron machine during measurements

A related problem is the assessment of the variation in the size of the slot relative to the angle of the crossing elements. And that the variation of the slot size is given by the formula

W=[d-(2*tol)]/tan(o) + [L-(2*tol)]/sin(o)

Where w is the width , d is the width of the vertical part, L the width of the horizontal part, and tol the value of the tolerance. Alpha (o) is the angle between the vertical and the horizontal elements. Finding this value is a precision aide in the modeling process, and it was to play an important role in the goal creating a flexible parametric model.

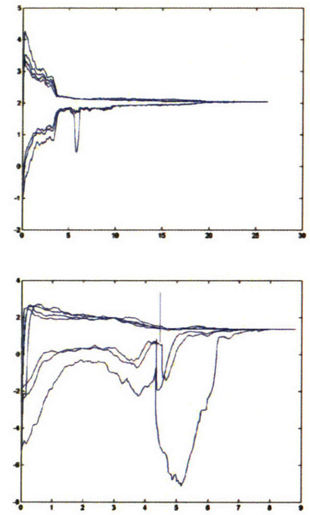


Figure 31. Strength vs. displacement charts of the different measured joints

3.2.3 Dealing with structural optimization

The generative grammar has room for structural improvement through three different strategies. Actual examples of structural adjustment for specific designs made with the grammar are outside the scope of this thesis. However in this chapter I provide open strategies for structural adjustments to take place in an object derived with the grammar.

It is worth noticing that material properties do not scale linearly. The structural behavior changes between scales even in objects of the same material. The optimal structural solution for a 1/8" thick plywood box at 1" = 1' is not the same to that for a 1" thick plywood at full-scale. An informed use of the strategies in this chapter can provide non-linear scalability to the system.

3.2.3.1 Modulation of the structure

By changing the distances between different structural elements, between the end of a structural element and the intersection with another element, and between the intersection of two structural elements and an end. The height of the structural element is also a defining factor of the structural performance of the object.

3.2.3.2 Parameters of the joint

The size and depth of the slots, which will affect specifically the resistance to certain lateral loads.

3.2.3.3 Substitution rules

A set of rules of substitution specific for certain elements is defined. These substitutions provide increased structural rigidity by breaking continuity of joint nodes along the structure (rule 1) or by conflating sheathing panels (rule 2).

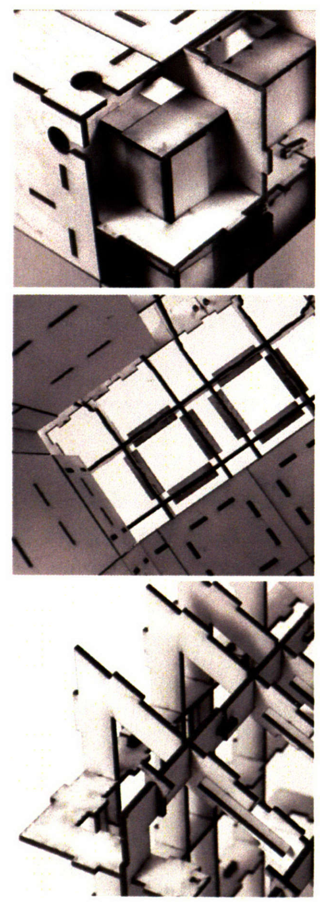


Figure 32. Finding the right tolerance in 1/8" Plywood

Any design generated by the sequential application of the grammar rules is constructible as the parameters for tolerance, thickness of materials, structural modulation, etc. are built in the members of the vocabulary. The structural performance of the objects that result of this sequential process of addition and subtraction is not, however, optimal. The "building blocks" of the grammar result in an inconvenient continuity of the connection nodes that increase the bending moments transversally to the continuity lines.

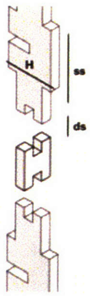
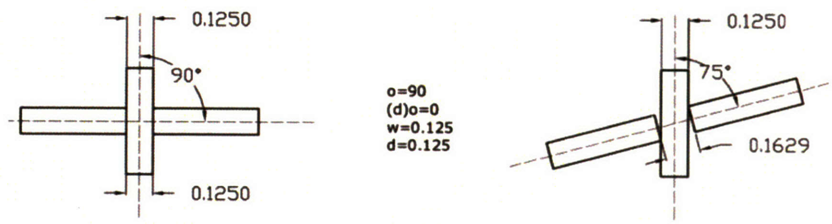


Figure 35. Structural modulation parameters

Figure 34. Variation of the slot size relative to the angle

Figure 36. Parameters of the joint diagram



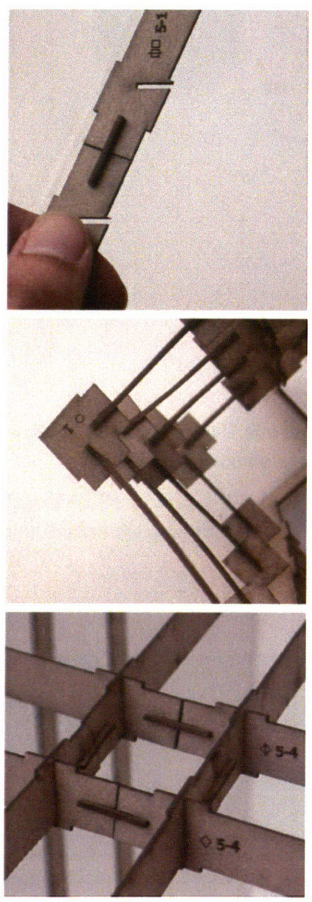


Figure 33. Finding the right tolerance in 1/16" chipboard

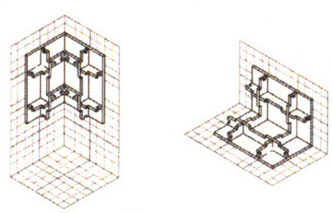


Figure 37. Examples of substitution rules for panels

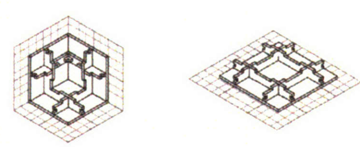
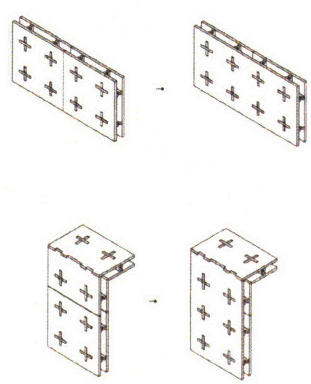
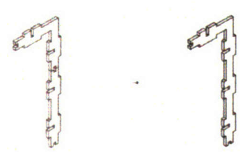


Figure 38. Examples of substitution rules for structure.





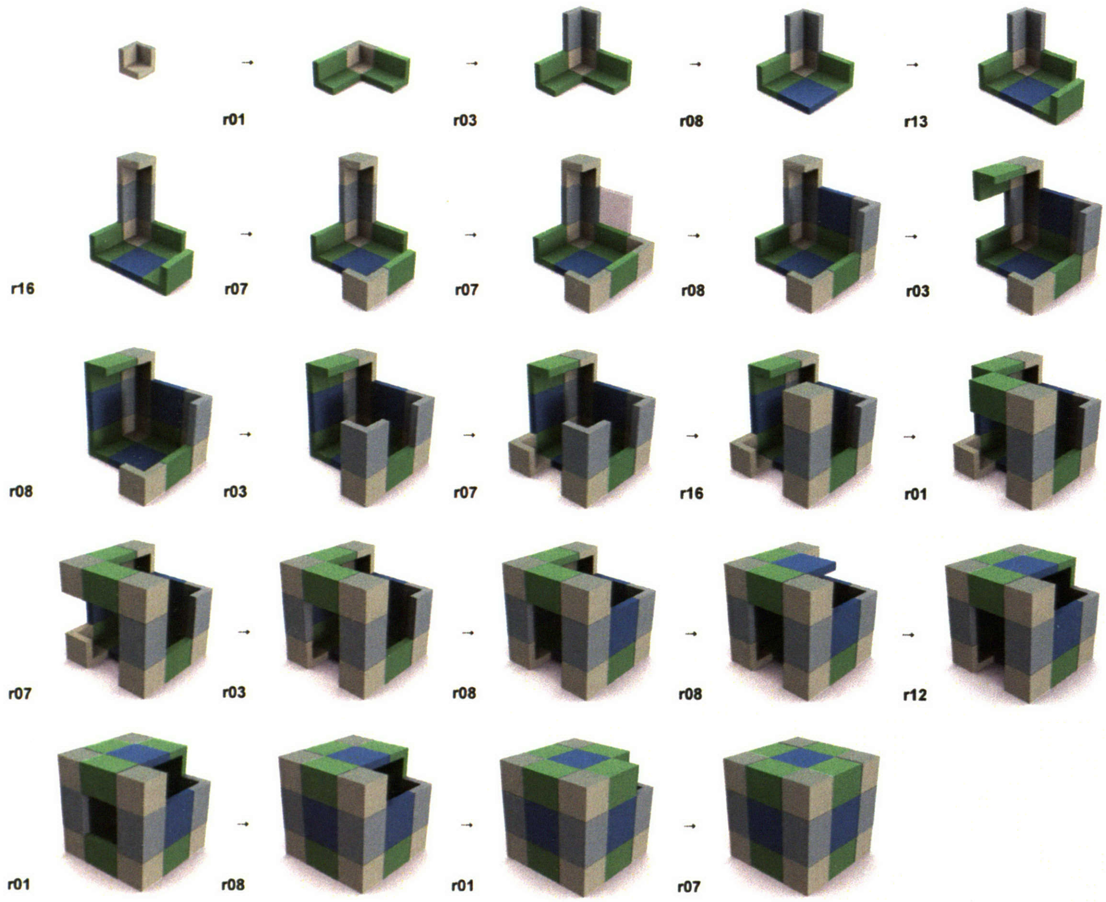


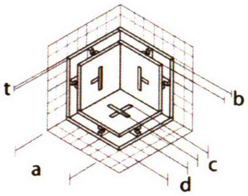
Figure 39. Deriving a design using the generative grammar

In this chapter I will show how the grammar can be used generatively to derive a specific design, and flexibly, to modify this design flexibly by adjusting the global geometry of the object.

3.3.1 Growth

It is the possibility of having open-ended design processes what makes this particular grammar generative. As rules of transformation are applied non-deterministically to the components, designs can change, grow, holes can be opened, and new sections may appear. The image shows the derivation of a very simple object, a closed box. It is worthy of noting that a pre-rational process with clear rules can be described computationally very easily by the sequence of rules that was used to derive the design.

There is an infinite number of different sequences of rules that can generate the exact same closed box, and there is an infinite number of design variations that can be performed on the object.

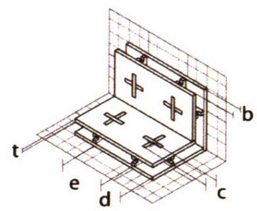


corner{cpanel(a), beamHeight(b), notch(c), thickness(t)}

cpanel > (notch + 2*(axis-edge))

axis-edge > notch

beamheight > (3 * thickness)

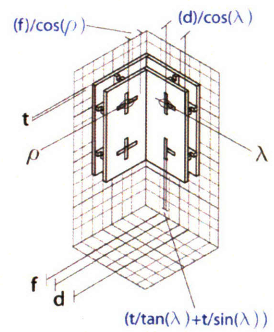


endWall{axis-edge(d), axis-axis(e), beamHeight(b), notch(c), thickness(t)}

axis-edge > notch

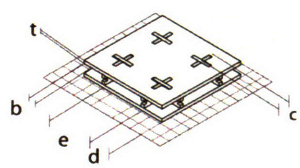
axis-axis > beamHeight

beamheight > (3 * thickness)



ArticulatedEndWall{ beamHeight(b), notch(c), thickness(t), run(n), angle1(λ) angle2(ρ)}

axis-edge > notch



wall{ beamHeight(b), notch(c), thickness(t)}

Figure 40. Parameters and relationships in the grammar

3.3.2 Flexibility

The generality of the description will afford the versatility of the system to operate at different scales and materials (for example 1/32" chipboard, 1/8" Plexiglas, or 1 inch plywood). The parameters taken into account in the grammar are a) Tolerance b) Thickness of material c) Size of the slot d) Distance between slot and end of the piece e) Depth of the slot f) Distance between slots.

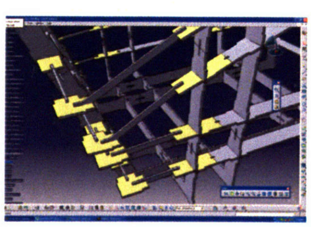


Figure 41. Image of the CATIA model on screen

CATIA software provides a framework to encode the dynamic relationships of dependency between the parameters described in section X. I built a model of the closed box derived with the generative grammar. In the model all the faces except the floor can be changed and moved.

Due to its very hierarchical nature (everything gets created as a branch of a large data tree and is either "children" or "father" of its neighbors) there is no simple way to use go back to the "generative level" and operate changes in the topology of the object. The model can, however, adapt easily to different materials and shapes.

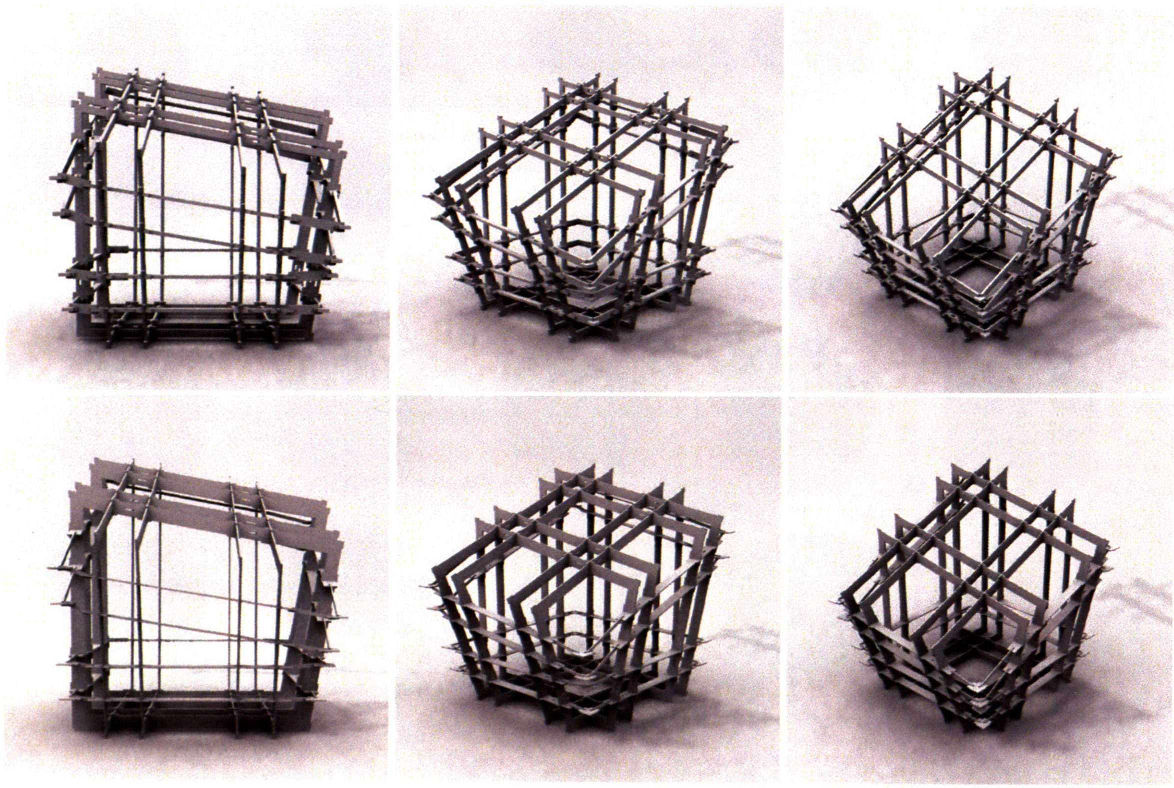


Figure 42a. Different parameterized structures for different materials: Plywood 1/8" thick (upper row) and Chipboard 1/16" thick (lower row). Notice the changes in the sizes of the structural elements

4 Conclusions

4.1 Design trade-offs

One of the many ways in which design can be seen is as a continuous bargain between the designer and the constraints, some of which are imposed by the problem given, others are found along the process of design exploration. I've focused in discussing the role that material constraints play in computational design environments, keeping in mind that these constraints are a narrow subset of a much larger universe of issues to consider in any –even a very simple- design process.

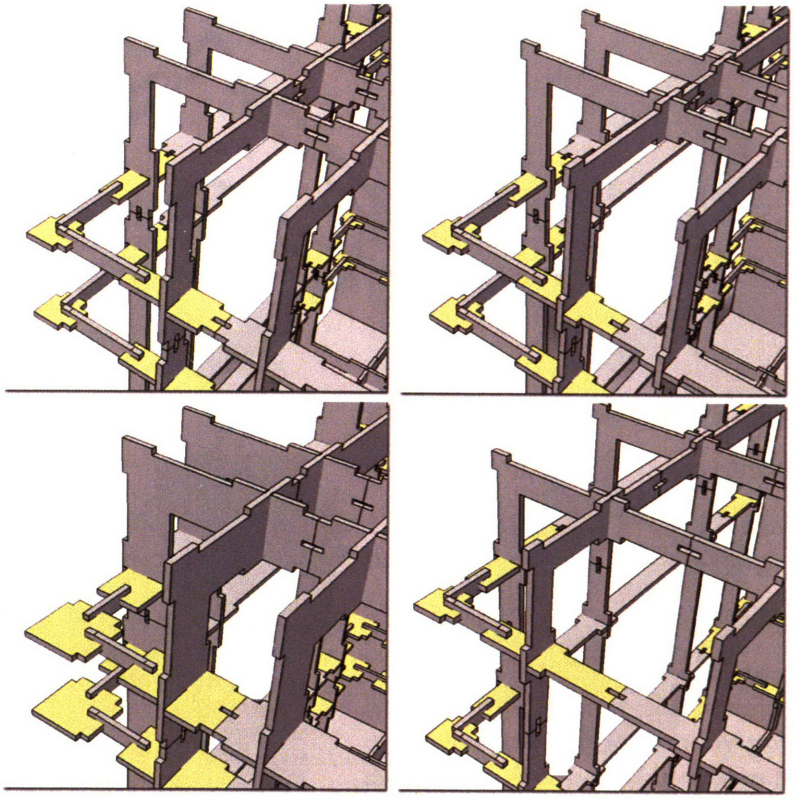


Figure 42b. Corner detail: The parameterization allows the model to adjust to different materials and structural modulations

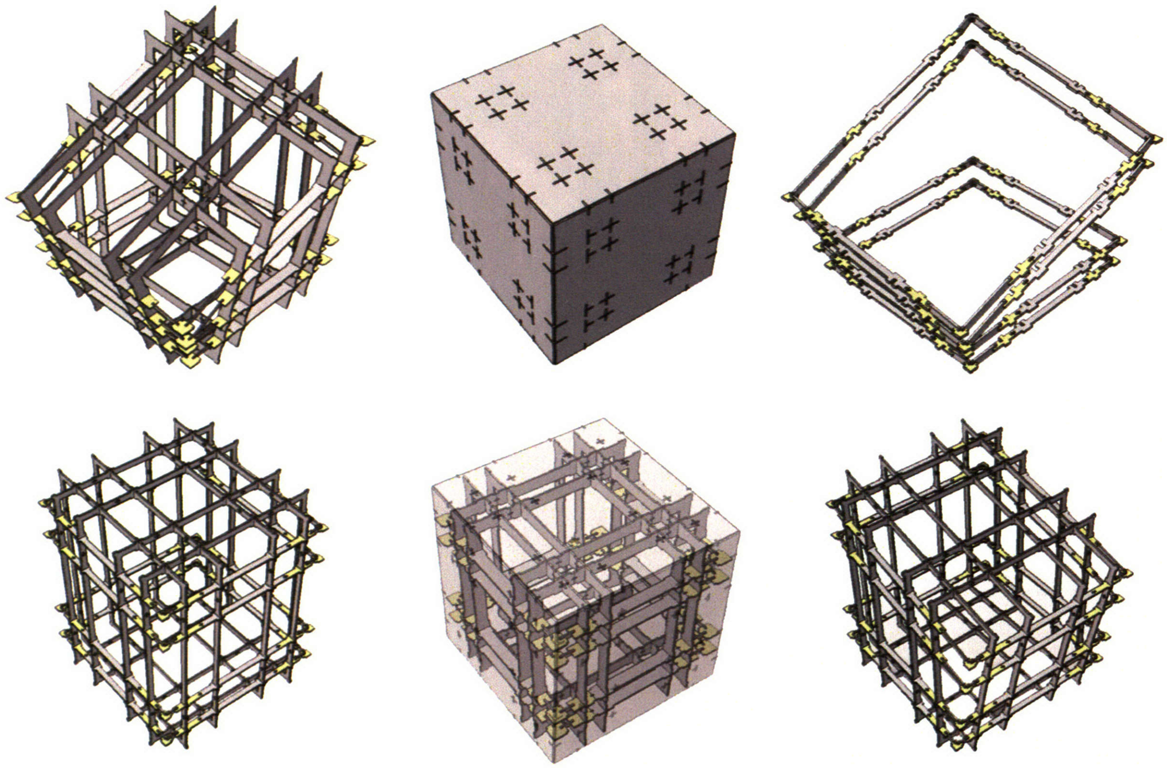
There is room for future development in computational design systems towards finding active ways to involve such constraints in design environments and dynamically explore material trade-offs.

4.1.1 Growth vs. Flexibility

Making small changes in the global shape of the design in a closed box is extremely time consuming using a solid modeling and drafting system (ACAD2007). In contrast, using a parametric model built in CATIA, the same changes can take a tenth of the time (Figure 46).

The trade-off lies in that the highly hierarchical and constrained nature of a parametric model makes it virtually impossible to organically "add" or "subtract" elements to the composition (a characteristic of a generative process): a box remains a box, even if we can change its angles or the properties of its elements. Architects who are familiar with parametric modeling often refer to this condition saying that the design ideas must be completely clear before starting a to model. In a way "there's no way back"; this is the price of a certain amount of global to local design flexibility.

In contrast, the non-hierarchical nature of solid modeling allows for addition and subtraction of elements (a typically generative or constructive approach), but the trade off lies in that there are no ways to propagate



changes across the composition.

Figure 42c. The elements of the grammar respond to global changes. The closed box can become almost any box.

4.1.2 Easy manufacturing vs. highly defined solution space

The prototypes show how a material and device dependent physical grammar can provide 1) a certain amount of design flexibility and 2) an optimal connection to fabrication technologies.

The parametric boxes show how this flexibility can be increased by defining mathematical relationships between the different dimensions of the elements and global parameters that relate the elements to specificities of the materials and other dimensions. As mentioned in the previous section,

They also show how the inherent geometrical and physical properties of the design language affect and characterize the language by limiting it.

It is clear that the boundaries of the language define a constrained world of shapes and variation. These boundaries can change substantially by manipulating the global parameters that control the structural and physical properties of the grammar. I was able to determine that for the material most used in the prototypes (1/8" thick plywood), the universe of "safe" designs that the grammar is defined by the set of volumes that

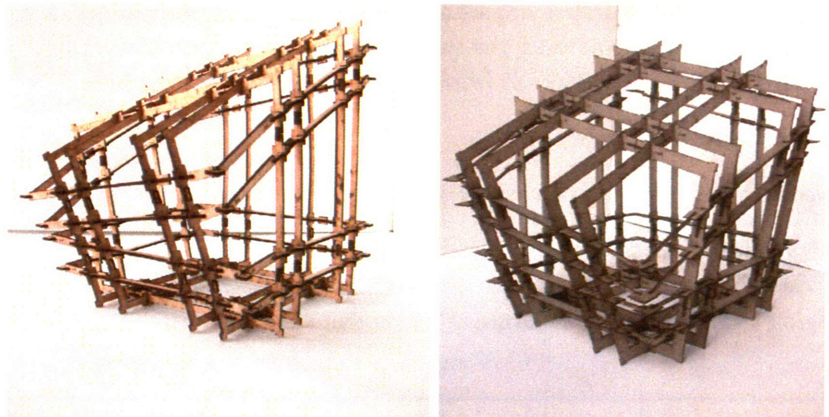


Figure 43a and b. Two structures of different materials and slightly different shape, adjusted and fabricated in under 10 hours from the parametric model. (No two components are the same)

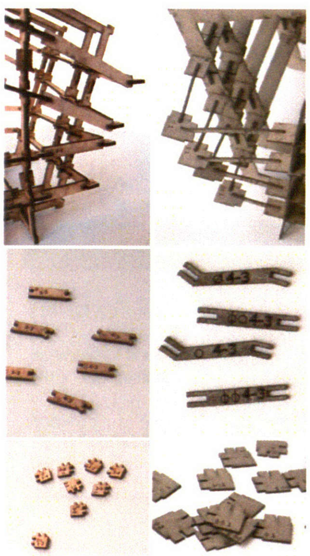


Figure 43b. The components are generated automatically by the model when the shape and/or material of the box changes.

comply with the following two conditions

- The angles described by the walls and the horizontal plane are greater than 80deg and smaller than 120deg

- The height of the box is at least 300mm

This is the inherent trade-off of facing a design problem with a design language fixed beforehand. This problem is usually described by the opposition between two mutually exclusive processes: post-rational and pre-rational. A post-rational process typically starts with a shape devoid of material considerations and then infers methods for it's construction; often a post-rational process involves rational subdivision of the "fluid" shape into components. A pre-rational process, in contrast, is a process where the construction technique is defined early in the design process, becoming a major constraint in the form-finding[10]. How fluid can building blocks be? How constructive can fluid shapes be? I hope that the experiments presented in the technical sections of this thesis provided useful insights into this question in the light of the current landscape of digital design and fabrication technologies.

4.2 Problems

4.2.1 Warping

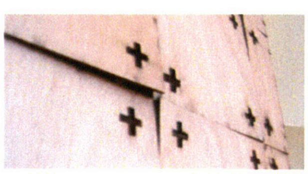


Figure 45. Example of warping in the panels of the closed box

Sheet materials distort from their original plane in a phenomenon known as warping. These distortions are caused by different factors such as humidity, temperature, and therefore are very impossible to fully predict in a digital model. Warping falls perfectly in the category of "sticky and inconvenient contingencies of dealing with physical materials".

Although the prototypes show that the structural elements of the objects derived with the grammar are able to self-correct the errors produced by the warping of the plywood sheets, this is not the case for the paneling,

10 See (Loukissas 2003:33)

and warping has a negative impact on the sheathing that needs to be addressed in order to advance the system (in an extreme case of warping the panels can tend to pop-out from their positions in the structure).

Possible solutions can be

- Additional joints that connect perpendicularly between panels

- A system where the panels instead of being fixed by friction can be "slide-in". Instead of fighting the warping with more material, acknowledging it and providing a margin of movement to the panels.

		Box 3	Param Box
Independent Variables	Shape	Cube w/angled roof and walls	Cube w/angled roof and walls
	Number of non-ortogonal edges	6	6
	Design Time (hr)	58	2
	Preparation for Fabrication Time (hr)	20	4
	Construction Time (hr)	15	3
	Total Time	93	9
Controlled Variables	Design Platform	AutoCAD 2007	CATIA V17
	Fabrication Device	Universal Lasercutter Bedsize: 32" x 18"	Universal Lasercutter Bedsize: 32" x 18"
	Material	Plywood 10 sheets of 24"x12"x1/8"	Plywood 10 sheets of 24"x12"x1/8"
	Designer	DC	DC

Figure 46. Comparative table showing the time saved by using the paramtertic instead of teh solid modeler.

4.3 To Explore

This thesis exposes the lack of an integrated software platform that simultaneously supports both growth and flexibility as design operations, and easy to implement material constraints.

A novel design tool can be outlined on the basis of this observation, a tool that is able to involve material knowledge in the early conceptual stages of design and keeps the design process constrained to the requirements of specific material and device concerns. The explorations conducted in this thesis suggest that in order to achieve this, the design tool needs to a) allow a designer to switch between different levels of representation (considering fabrication-ready information as one of these levels), b) allow for both local and global dynamic design variation c) have a detailed and extensible construction knowledge-base.

4.4 Contributions

- A generative grammar for manufacturing 3D objects from sheet materials that

o Is based solely on friction

o Can be scaled in a non-linear manner. (Material properties do not scale linearly)

o Can be used with different materials

o Can grow, and can be flexibly changed

- An alternative to post-rational views and strategies in digital design and fabrication.

- The outline of a material and device-specific design tool.

5 Discussions

5.1 Reacting to the dualism

In this thesis I have drawn a generative grammar for 2D manufacturing of 3D objects as an antidote to what I feel are the excesses of too exclusively post-rational approaches to design and construction in the current practice of digital design and fabrication. I have framed these post-rational approaches within a long standing separation in architectural and philosophical thought between design and construction, and between mind and body.

Figure 47. The primitive hut

The dangers of taking the dualism too seriously have been addressed in different ways through architectural history. In this section I propose a reading of Le-Duc's critique of beaux-artism as a reaction to the excesses of a non-productive dualism between the design and the construction world.

Viollet Le-Duc (1814-1879), sees a crisis in the architecture of his time caused by the adoption of the purely formal aspects of classic buildings as the raison d'etre of architectural education, without regard to the physical principles that underlie it. His harsh critique of the French Ecole des Beaux Arts consisted in a set of material principles that he discerned and that –according to him- could be applied universally to the design of any building, at any time, and that would –in terms of M.F. Hearn-, "make it possible for architecture to transcend the stale academicism of the Ecole des Beaux Arts" (Le-Duc 1990).

These principles, fundamental to Le-Duc's theory, were found trough his extensive study of gothic architecture in France, which he interpreted not as a mystical or iconographical pursuit, but as a result of the evolution of a technique aimed at building higher and higher vaults. Le-Duc's interpretation of the first, primitive hut embodies romantically his view of structural principles and understanding of materials, and necessity, as the only valid design drivers.

By rethinking architectural theory in terms of material and structural principles Le-Duc eliminates other narratives (historic, religious, etc.), laying out an important part of the foundations of modern architecture.

In a more recent reaction to the excesses of the dualism, in Architecture and the crisis of modern science, Alberto Perez Gomez draws a similar argument focusing on the disembodiment of knowledge that comes with the excesses of scientific thought.

A simplistic view of human experience, derived from the projection of scientific models onto human reality, exemplified by certain aspects of behaviorism and positivistic psychology, has hampered our understanding of the essential continuity between thought and action, between mind and body. (Perez-Gomez 1983)

Computational design systems are largely an expression of these projections, and the dualism is engrained both in the systems and in the cultural practices that establish the interaction between designer and tool.

5.2 Design software culture

The professional role of the designer in today's culture is inseparable from the closed simulated worlds that serve as media for creating spaces and artifacts. The nature of these simulations as socially constructed objects is worthy of examination. Tools, and particularly computing, are not neutral and embody a discourse that has cultural, political and social dimensions[11].

Software packages for design offer an increasingly large repertoire of tools that allow for different kinds of control in the generation of previously unthinkable virtual shapes. Design tools have come to encode geometric knowledge to the point that no particular training is required to create complex surfaces and solids inside the screen. Software packages like AutoDesk Maya were developed for the movie industry and were later adopted by architects and designers seeking to transcend the form-making constraints of traditional CAD systems. As Manuel De Landa has noted, when computational design environments transcend the automation of hand-based processes, and start incorporating ways of interacting with design entities that respond to different rules and algorithms, they behave in a different and less predictable way than other, more traditional descriptions (De Landa 2001). In some cases the signature of the software becomes a strong feature of the design, exposing a displacement of authorship and professional roles in design that needs to be subject to another study.

11 This has been pointed out by historians of technology such as (Edwards 1996 and Mahoney 2001)

Computational tools and the cultural practice of their use support the established notion of design as a process separate from matter, this is visible in some of the examples used in previous sections, where the less the designer has to deal with material constraints the freer she/he is assumed to be.

Also important, the more behavior the tool is able to offer, the more specialized the designer needs to be, and the more distant she or he will be from the materiality of the real construction. A quick examination of the trends of the current design, both in academia and in practice, will yield –with exceptions- an increasingly difficult strive of designers to impose the fluid geometry of forms created in 3d environments into the materials.

The increasing number of practices that place themselves as bridges between the complexity of digitally generated shapes and the reality of materials shows how this conceptual distance between the materiality of descriptions and the materiality of buildings is requiring new skills and social roles[12].

The lack of computational tools that successfully integrate the generative and the flexible forms two very distinct "families" of computational environments, two closed worlds that do not communicate easily. This separation is yet another obvious manifestation of the traditional gap between the architect and the engineer, and the corresponding difficulties in the integration of technical subjects in design curricula.

Can we speak of the graphic mannerisms of screen-based design practices as a new canon, comparable to the classic canon referred to as "stale-academicism of form" by Le-Duc's perception of French beaux-artism? (Le-Duc 1990) Can we devise an alternative starting premise for computational design systems?, a premise in which a dynamic dialogue between materials and form is a defining feature of our aesthetic judgments on architecture and therefore of our understanding of "design"?

12 While I work on this document Fabian Scheurer, a German architect and computer scientist, gave a lecture to the Design and Computation Group at MIT's School of Architecture in a nearby room. Designtoproduction, his practice, is defined by him as "a consultancy for the digital production of complex designs", further more, he described his team as integrating "specialist knowledge from various fields to help architects, designers, engineers, and manufacturers bridge the gap between idea and realization" (emphasis added). A few weeks later Paul Seletsky gave a lecture on the same room, to the same audience, in which introduced an agenda for a methodological integration of performance data in the early stages of conceptual design, a sort of "consortium" project involving schools and software development teams such as Gehry Technologies. The project involves finding a pre-rational and performance based approach to digital design.; the argument drew largely on the convenience of blurring the line between different computer analysis (Ecotect), and design systems (Digital Project, Rhino).

6 References

Alberti, Leon Battista
1988 On the Art of Building in Ten Books. Trans. Joseph Rykwert with Neil Leach and Robert Tavernor. Cambridge: MIT Press, 1988.

Bentley, Peter, and David Corne, eds.
2002 Creative Evolutionary Systems. San Francisco: The Morgan Kaufmann Series in Artificial Intelligence.

Botha, Marcel
2006 Customized Digital Manufacturing: Concept to Construction Methods across varying product scales. M.S. Thesis. Department of Architecture. Massachusetts Institute of Technology.

Coons, Stephen
1966 Computer, Art & Architecture. Art Education, Vol. 19, No.5 (May,1966), 9-11

DeLanda, Manuel
2001 Philosophies of Design: the Case of Modeling Software. Verb: Architecture Bookazine. Madrid: Actar Press.

Edwards, Paul N.
1996 The closed world: computers and the politics of discourse in Cold War America. Cambridge, MA: MIT Press.

Evans, Robin
2000 The Projective Cast: Architecture and its Three Geometries. Cambridge: MIT Press.

Frampton, Kenneth
1995 Studies in tectonic culture: The Poetics of Construction in Nineteenth and Twentieth Century. Cambridge: MIT Press.

Gershenfeld, Neil
2005 FAB: The Coming Revolution on Your Desktop--from Personal Computers to Personal Fabrication. New York: Basic Books.

Griffith, Kenfield
2006 Design Computing of Complex-Curved Geometry using Digital Fabrication Methods. M.S. Thesis, Department of Architecture, Massachusetts Institute of Technology.

Gross, Mark
1996 Why can't CAD be more like LEGO? CKB, a program for building construction kits. Automation in Construction 5, 285-300.

Gross, Mark Donald
1985 Design as exploring constraints. Ph.D. dissertation, Department of Architecture, Massachusetts Institute of Technology.

Gero, Jean, and Udo Kannengiesser
2004 The situated function-behavior-structure framework. Design Studies 25, 373-391.

Helmreich, Stefan
1998 Silicon Second Nature. Berkeley and Los Angeles CA: University of California Press.

Heyman, Jacques
2003 Wren, Hooke and partners. Paper presented at the First International Congress on Construction History, Madrid, 2003.

Ingold, Tim
2001 Beyond Art and Technology: The Anthropology of Skill. In Anthropological Perspectives on Technology. Michael Brian Schiffer, ed. Pp. 17-31. Amerind Foundation Publication.

Seely, Jennifer CK
2004 Digital Fabrication in the Architectural Design Process. M.S. Thesis, Department of Architecture, Massachusetts Institute of Technology.

Knight, Terry
2000 Shape Grammar in Education and Practice: History and Prospect. The International Journal of Design Computing vol. 2 (1999–2000).

Lang, S.
1965 De Lineamentis: L. B. Alberti's Use of a Technical Term. S. Lang. Journal of the Warburg and Courtauld Institutes, Vol. 28. (1965), pp. 331-335. Stable URL: http://links.jstor.org/sici?sici=00754390%281965%2928%3C331%3ADLLBAU%3E2.0.CO%3B2-Q

Le-Duc, Viollet
1990 The Architectural Theory of Viollet-le-Duc: Readings and Commentaries (Paperback). Hearn, M.F. ed. Cambridge: MIT Press.

Loukissas, Yanni
2003 Rulebuilding: Exploring Design Worlds through End-User Programming. M.S. Thesis, Department of Architecture, Massachusetts Institute of Technology.

Loukissas, Yanni
N.d. The cultural history of the digital fabrication studio. Unpublished, Department of Architecture, Massachusetts Institute of Technology.

Mahoney, Michael S.
2001 Boys' toys and women's work : feminism engages software. In Feminism in twentieth-century science, technology, and medicine. Angela N.H. Creager, Elizabeth Lunbeck, and Londa Schiebinger, eds. Chicago: University of Chicago Press. Available online at <http://www.princeton.edu/~mike/boystoys.htm>. [Accessed Feb 2007.]

Mitchell, William
1990 The Logic of Architecture: Design, Computation and Cognition. Cambridge: MIT Press.

Mitchell, William J., and Malcolm McCullough
1995 Digital Design Media. New York: John Wiley & Sons Inc.

Oxman, Rivka
1997 Design by re-representation: a model of visual reasoning in design. Design Studies

18, 329-347.

Perez-Gomez, Alberto
1983 Architecture and the crisis of modern science. Cambridge: MIT Press.

Popescu, George, with Patrik Kunzler and Neil Gershenfeld
N.d. Digital Printing of Digital Materials. Unpublished.

Popescu, George, with Tushar Mahale and Neil Gershenfeld
N.d. Digital Materials for Digital Printing. Unpublished.

Reddy, Michael
1979 The Conduit Metaphor. Metaphor and Thought. A. Ortony. Cambridge, Cambridge University Press.

Sacks, Rafael, with Charles Eastman and Ghang Lee
2004 Parametric 3D modeling in building construction with examples of precast concrete. Automation in Construction 13. 291-312.

Sass, Lawrence, with Kristina Shea and Michael Powell
2005 Design Production: Constructing free form designs with rapid prototyping. Paper presented at the ECAADE conference, Portugal, September 21.

Sass, Lawrence
2007 A Physical Design Grammar: A Production System for Layered Manufacturing Machines. Unpublished.

Sass, Lawrence
2005 A Wood Frame Grammar: A generative system for digital fabrication. International Journal of Architectural Computing, Volume 4, Number 1, January 2006, pp. 51-67(17)

Sass, Lawrence, and Rivka Oxman
2006 Materializing Design: the implications of rapid prototyping in digital design. Design Studies 27 325-355.

Stiny, George
1985 Computing with form and meaning in architecture. Journal of Architectural Education, 39(1) 7-19.

Stiny, George, and James Gips
1978 Algorithmic Aesthetics: Computer Models for Criticism and Design in Arts. University of California Press, Berkeley and Los Angeles, California.

Stiny, George
1980 Kindergarten Grammars: designing with Froebel's building gifts. Environment and planning B7, No.4, 409-462.

Stiny, George, and Lionel March
1981 Design Machines. Environment and Planning B: Planning and Design 8(3) 245 – 255

Suchman, Lucy
1987 Plans and Situated Actions: The problem of human-machine communication. Cambridge University Press.

Sutherland, Ivan
1963 Sketchpad: A man-machine graphical communication system. Ph.D. dissertation, School of Electrical Engineering and Computer Science, Massachusetts Institute of Technology.