Process Bifurcation and the Digital Chain in Architecture

THÈSE N^O 5459 (2012)

PRÉSENTÉE LE 14 SEPTEMBRE 2012

À LA FACULTÉ DE L'ENVIRONNEMENT NATUREL, ARCHITECTURAL ET CONSTRUIT
EPFL LABORATOIRE BÂLE
PROGRAMME DOCTORAL EN ARCHITECTURE ET SCIENCES DE LA VILLE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

PAR

Russell Alexander LOVERIDGE

acceptée sur proposition du jury:

Prof. M. Andersen, présidente du jury
Prof. H. Gugger, directeur de thèse
Prof. Ph. Block, rapporteur
Prof. M. Pauly, rapporteur
Dr C. Schindler, rapporteur

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Suisse
2012

Abstract

This thesis investigates the impact of digital technology on the methods of design and production in architecture. Through research of history, theory, technology, and methods, the work determines whether the current use of new technologies should be considered as iterative development of the architectural practice, or as a radically new paradigm.

The computer has now matured into the primary working medium for architectural design. Digital tools are increasingly expanding their role, from design and visualization, to use in empirical simulation and evaluation, digital fabrication, and in on-site construction validation. This combination of linked tools, into a single project-wide solution system is called the "digital chain". This procedure is a significant opportunity for optimization of process, but it can also be seen as a catalyst to reinforce creative collaboration between disparate professionals in a design team. Because of this change to both methods and relationships the digital chain, and its components are understood to be *disruptive technologies.*

The *digital chain* has caused a *bifurcation* in architectural productivity, because of this disruption many theorists and critics claim that digital technologies now define a new era of architecture. This thesis seeks to understand if this inflection can also be considered a new *paradigm.*

The contemporary computer, as an "information machine" is characterized by three specific capabilities: *control, prediction, and processing.* Research and project work to examine the digital chain have been undertaken and categorized using these three investigation channels. Each topic for investigation has been instigated with a pedagogic work. Thereafter, additional "proof of concept" projects have been undertaken to advance the work to the professional level. The results and findings occur at two levels: Practical production of architecture, but also as conclusion about "digital learning" and the scope of technological adoption within the architectural profession.

The conclusions of the thesis state that a technologically induced paradigm-shift in architecture has *not* occurred. The current implementation of digital tools still only qualifies as iterative innovation of traditional methods.

The technology and use of digital tools in architecture has developed significantly in the last decade. Emerging technologies, new methods, and the prognosis for future developments will have significant effect on architectural design and production. Because architecture has a well established precedent of "re-purposing" technology from other disciplines, the thesis concludes that there is strong potential that a paradigm-shift may yet happen. By examining emerging innovations from other industries it is possible to make highly informed predictions about incoming innovations in materials, production methods, and conceptual systems. This insight into the next wave of potential catalytic influences is presented in the discussion, and it is concluded that a broader range of new innovations may yet invoke a technologically driven paradigm-shift in architecture.

Keywords:

Digital chain, digital fabrication, algorithmic design, reflective practice, paradigm.

Résumé

Cette thèse étudie l'impact des technologies numériques sur les méthodes de la conception et de la production en architecture. À travers des recherches dans l'histoire, la théorie, la technologie et les méthodes, cette œuvre cherche à déterminer si l'utilisation des nouvelles technologies doit être considérée comme un simple développement itératif de la pratique architecturale courante, ou comme un paradigme radicalement nouveau.

Avec le temps, l'utilisation des ordinateurs s'est transformé pour devenir le moyen principal de travail pour la conception architecturale. Le rôle des outils numériques en architecture est en train de s'élargir constamment. Ils sont de plus en plus utilisé pour le support de conception complexe telles que la visualisation, la simulation, l'évaluation, et la fabrication numérique. Cette combinaison d'outils reliés créant un seul système de solution à l'échelle du projet est appelé « la chaîne numérique ». Ce système présente une opportunité importante pour l'optimisation des processus, mais il peut aussi être vu comme un catalyseur de renforcement de collaboration entre les divers corps de professionnels au sein d'une équipe de conception. Grâce aux changements de méthodes et de relations simultanément, la chaîne numérique et ses composants sont considéré comme des « technologies de rupture ».

La chaîne numérique a provoqué une bifurcation de la productivité en architecture. En raison de cette perturbation, beaucoup de théoriciens et de critiques affirment que les technologies numériques ont provoqué une nouvelle paradigme dans l'architecture. Cette thèse vise à comprendre si ce changement de voie peut être vraiment considéré comme un nouveau paradigme en architecture .

L'ordinateur actuel, vue comme « machine d'information » est caractérisé par trois capacités spécifiques: gestion, prévision, et traitement. Pour cette thèse, les travaux de recherche et des projets visant à examiner la chaîne numérique ont été entrepris et classées à l'aide des trois canaux d'enquête cités ci-dessus. Chaque sujet d'enquête a commencé avec un travail pédagogique. Par la suite, des investigations complémentaires et des projets visant à éprouver les concepts ont été entrepris pour porter le travail à un niveau professionnel. Les résultats et les conclusions se situent à deux niveaux: d'abord par rapport à la pratique de la production architecturale, mais aussi au domaine de « l'apprentissage numérique» et la portée de l'adoption de ces technologies au sein de la profession d'architecte.

Les conclusions de la thèse montrent qu'un changement de paradigme en architecture induit par la technologie n'a pas eu lieu. L'utilisation actuel des outils numériques dans la branche peut être encore qualifié comme des innovations itératif par rapport à des méthodes traditionnelles.

La technologie et l'utilisation des outils numériques dans l'architecture s'est considérablement développé pendant la dernière décennie. Les technologies émergentes, les nouvelles méthodes, et les prévisions de l'évolution future auront des effets significatifs sur la conception et la production architecturale. Parce que l'architecture a un précédent bien établi « d'adopter et adapter » les technologies d'autres disciplines, cette thèse conclut qu'il est fort possible que ce changement de paradigme au sein de la profession peut encore arriver. En examinant les innovations issues d'autres industries, il est possible de prévoir avec précision des changements à venir dans les matériaux, les méthodes de production, et les systèmes conceptuels. Cet aperçu de la prochaine vague de potentielles influences catalytiques est aussi présenté dans la discussion de la thèse, et il est conclu qu'un plus large éventail d'innovations technologiques peut encore provoquer un changement de paradigme dans l'architecture.

Mots-clés:

chaîne numérique, fabrication numérique, conception algorithmique, paradigme, technologies de rupture

Acknowledgements

This work has only been possible due to the support and involvement of many people who shared my enthusiasm, gave me critical advice, provided encouragement, and who supported me in many ways through the years of investigation, writing, and production.

Here, I would like to express my thanks and gratitude to them:

Professor Harry Gugger, who gave me the opportunity and freedom to undertake this research with a free hand, and whose confidence in my work allowed me to approach this topic in an unconventional manner.

The members of the thesis jury: Prof Dr Marilyne Andersen, Prof Dr Mark Pauly, Prof Dr Philippe Block, and Dr Christoph Schindler; many thanks for your critical insight, support, and willingness to take part in this extensive process.

I extend my gratitude and thanks to my colleagues of the lapa and at the EPFL and ETHZ, for their support, input, and critical advice.

Specific credit and many thanks are extended to Dr. Kai Strehlke and Dr. Hani Buri for their camaraderie, assistance and invaluable input to the development of thesis ideas, research, and project work. Additional particular mention should be made of: Ralf Blättler for keeping me grounded in architecture; Mitch Heynick for friendship, support, and critical reflection with regards to issues of software and fabrication; François Perrin for assistance with fabrication and construction of prototypes; Pascale Luck for assistance with translations; and to all my other working colleagues within lapa for their on-going camaraderie, encouragement, and interest in my research.

As much of the work has an immediate connection to the classes taught during my time at both the ETH Zürich and the EPF Lausanne, I would also like to thank all of my former students for their participation, ideas, work, and willingness to engage in experimentation.

Finally I must acknowledge my family and friends.

To my dear friends Kevin, Sheila, Margaret, and Theodore Purkiss, for always providing enough in the way of distractions and amusement.

Many thanks to my in-laws: Prof. Dr. Herbert Lang, Maria Lang for their support and encouragement.

To my parents, Joan and Dale, as well as my siblings: Patty and Peter and their partners Cindy and Lee; thank you for your ever present love and continual support over great distance. Your encouragement, discussions, and occasional “kitchen table debates” provided much incentive to pursue and amalgamate both the creative, and the scientific world-views in my work and research; something that I hope has clearly manifested itself into this thesis.

…and finally, to my wife, Katarina. This thesis is only possible because of your love, patience, incredible tolerance, encouragement, support, and regular head massages when my brain was full. Without you this entire process would not have been possible. I love you dearly.

RAL - 10.5.2012

Forward

This thesis seeks to analyse the current position of architectural design methodologies within the context of emerging digital technologies.

Over the last five years of working in the laboratory of architectural production (lapa) we have developed and refined a methodology used in our design studio. The method follows three main stages of development; first *investigative*, then *creative*, and finally *reflective*. The procedure first focuses on determining the influencing issues from a wide contextual analysis of a specific design problem; this is an inherently objective and rational process. Following from this there is substantial understanding of the contextual issues, which allows for informed synthesis and design of detailed interventions; this is a highly subjective and creative process. Finally an evaluation of the design results is done so as to verify the original idea and to validate the "proof of concept". This final task begins with an objective assessment, but what is curious is that because of the experience of synthesis, the end evaluation is already a divergent process; producing new ideas of possibility, and improvements to the design.

This methodology gives a designer a broad understanding of the complex and interconnected sets of components, relationships, and parameters that affect a design. But the method is also aimed at creating a critical awareness of process. This method was developed on the idea of "systems thinking" and the ability to deal with increasing complexity in design and production.

For this doctoral work I have "cursed" myself in attempting to follow this methodology at multiple levels; both for the practical experimentation and for the philosophical and analytical development and presentation. I say "cursed" as *systems thinking* is defined by a spatial network of concepts, each with multiple links to others; this is a counterpoint to analytic methods of linear refinement. As such, it has been exceptionally difficult to create a thesis text where the disparate concepts, experiments, parts and sections can be seen to interrelate with each other as nodes in a highly complex network. This mode of thinking and this model for a thesis are directly opposed to the linear narrative of a traditional thesis. The result of this may be verbose, and also complicated just like the topic. I humbly acknowledge the irony of this situation, beg the reader's indulgence, and offer apologies in advance.

The thesis is organized into five main parts: The opening section introduces and explores the nature of the thesis question: What is a measure and method for determining a paradigm shift in innovation? The second section focuses on technology and the current state of digitally produced architecture. The third section investigates history and theory, so as to position technology and relate it to architectural design and production. The fourth section illustrates the use of technology through the description of several experimental projects, with focus on three main themes of *control, prediction,* and *processing*. The final section develops the conclusions for the thesis, and makes prognoses for future developments and work.

The fact that the thesis disproves the initial assumption of a "new technological paradigm" is in my opinion a temporary state, given that as technology evolves, so too will its use in architecture. As such this doctoral dissertation should be understood as a temporal "snapshot", and I look forward to the changes and innovations in architecture to come.

R.A.L. - 10.5.2012

Table of contents

(cont.)

Table of Contents (cont.)

"You think philosophy is difficult,…

…but I tell you, it is nothing compared to the difficulty of being a good architect."

Ludwig Wittgenstein[1]

[1] Ludwig Wittgenstein, as quoted in: Botton, A. (2006). *The Architecture of Happiness*: p.26

1. Exposition

1.1. Hephaestus as myth

> *"Sing, clear voiced Muse, of Hephaestus, renowned for his inventive skill, who with grey-eyed Athena, taught to men upon earth arts of great splendour, men who in former days lived like wild beasts in mountain caves. But having learned skills from Hephaestus, famed for his work and craftsmanship, they now, free from care, peacefully live year by year in their houses. Be gracious, Hephaestus, and grant me excellence and prosperity."*
>
> -Homeric Hymn 20: to Hephaestus et alia[1]

Hephaestus, the mythological son of Hera, Queen of the Gods, was born clubfooted and lame, thusly making him a grotesque blight of imperfection to the godliness of Olympus. At his birth, His mother Hera, being repulsed and shamed by his deformity, cast Hephaestus out of the heavens in disgust. Legend says that he fell for a day and a night before smashing into the sea. He was rescued and landed on the Greek island of Lemnos, where he was cared for and raised by the Nereids.

On Lemnos he spent the ages learning to be a master craftsman. Hephaestus built a great forge and workshop under the once volcanic mountains of the island, and for this he is appointed the god of useful fire (and is known in his Roman guise as Vulcanus).

In an act of revenge against Hera for rejecting him, Hephaestus crafted her a magical golden throne, which when she sat upon it, trapped her and did not allow her to stand. The other gods in desperation begged Hephaestus to return to Olympus to release their queen go, but he refused in saying "I have no mother". Finally Dionysus, is sent to bring Hephaestus back to release her, making him the only god said to have returned to Olympus after exile.[2]

Despite his handicap and his "less than perfect" appearance, the gods finally accept Hephaestus into the pantheon because of the skills he possesses. Here he assumes the role of "maker" to the gods. In addition to his own home and workshop; "the preeminent house of the gods"[i], Hephaestus creates many of the powerfully imbued pieces of architecture and equipment that appear in Greek myth: The polished colonnades for Zeus's house, the unbreakable doors of Hera's chamber, the twelve golden thrones of the gods, Hermes' winged helmet and sandals, the fearsome Aegis breastplate, Aphrodite's magical girdle, Achilles' armour, Helios' chariot, Eros' bow and arrows, and the thunderbolts for Zeus.

In his labours Hephaestus is assisted by the three Cyclops brothers, who were his workmen. Hephaestus represents willpower and intelligence, whereas his workmen represent the unintellectual strength and power. Additionally, because of his lameness Hephaestus creates twenty "automatons" in the form tripods of metal equipped with animated tools to follow his instructions[ii]. It is only through the combination of intelligence, power, and innovation that elegance of design can be implemented into fabrication.

To this day, Hephaestus is worshipped in the manufacturing and industrial centres of Greece as the god of blacksmiths, craftsmen, artisans, and most importantly as the god of technology.

1.2. Hephaestus as change

The parallels between the myth of Hephaestus and the role of technology in the history and development of architecture are both ironic and exemplary.

Design as a process, alternates between the subjective talents of artistry and the objective requirements of purpose. Different practitioners place variable emphasis on the balance between these two determinants, creating variety in projects. It is in this variability of balance that individuality, creativity, and expression are found in design.

---

[1] In: H.G. Evelyn-Whyte, (trans.), "*Hesiod, the Homeric Hymns, and Homerica*": p.447

[2] Pausanias, *1.20.3*.

Technology, like its god Hephaestus, has been at different times both rejected and lauded. Hephaestus himself is declared unworthy because of his incongruity with conventions and expectations of godliness. This rejection, however, becomes the driving force in the development of his skills, and it eventually enables him to prove his inner worth as an equal to the other gods. A review of architectural history shows periods and eras where technology is clearly a driving factor in development, innovation and style, but also there are other times where technology is merely subservient to design.

The inherent and subjective talent and artistry of a designer is unquantifiable and unpredictable by nature. If the potentials of talent are abstractly equated with the magical powers of the gods, then the myths of the inventions of Hephaestus shows that even these special abilities can be augmented by the objectively designed and crafted implements of technology. The fact that Hephaestus's creations are also imbued with artistry and beauty should however not be overlooked, as the value of the implement extends beyond both function and form.

Hephaestus's legend proves him to be a master or his own condition; of being both skilled but also disadvantaged. His creation of automatons; mythological robots equipped with tools to do his bidding, compensate for his disability, but they also enhance his abilities in other ways. The power of Hephaestus as a "maker" combines with technology as an enabler, to augment existing powers, resulting in an amplification of both function and beauty.

Finally there is a subtext to the myth that should not be overlooked; Hephaestus personifies the values of "inner character or inner beauty", but also the value of work, determination, and innovation. His story demonstrates the strength of transforming a destructive power into a benevolent and creative one, and how to find the positive, responsible and efficient creativity in the tasks at hand. In establishing these productive values, the act of innovation itself is shown to be the equivalent of the beauty, perfection, and powers of the other gods.

Architecture through history has also undergone cycles where different balances between artistry and technology prevail. Specific points of innovation define many of the milestones in the development of architecture, but these innovations themselves are a product of many obscure parameters, factors, and variables of history. The return of Hephaestus to Olympus brought unequalled craftsmanship and technology to the gods, but this skill and knowledge was a by-product of his experiences. The ensuing inventions of Hephaestus enabled plot progression of the most revered myths, but it needs to be remembered that his skills are not magics, but rather they come from by the Sintians; the learned craftsmen who originally taught him. The incorporation of skilled design and magical inventions fundamentally changed the paradigms of mythology, much as technological innovation continues to reshape and redefine architectural paradigms in reality.

This thesis work investigates technology and its potential for change; both changes of capability and productivity, but also changes of mind-set and understanding. Technology as a force for change finds its roots in creativity and invention; it is empowered by its own inspiring capacity, and its impact can be fundamental and immediate: three facts that have had direct influence on the evolution of architecture. This thesis investigates digital technologies as they relate to both the pragmatic and theoretical aspects of architecture with the goal of understanding the current situation and setting strategy for architectural development in the future.

---

[i] From: Homer, *Iliad Book 18*.370-376 - This passage describes the house of Hephaestus as" wrought with bronze and covered in stars. In the house Hephaestus is making tripods at his forge."

[ii] From: Aristotle, *Politics*, 1253b - Hephaestus created tripods that '"enter, self-moved the company divine" Aristotle includes this remark in a discussion of the need for assistance to craftsmen whose tools, unlike Hephaestus' tripods, would not work on their own.

2. Thesis

2.1. Introduction

2.1.1. Bifurcation

> *"…when a system switches from one stable state to another stable state (at a critical point called a bifurcation) minor fluctuations may play a crucial role in deciding the outcome. Thus, when we study a given physical system, we need to know the specific nature of fluctuations that have been present at each of its bifurcations; in other words, we need to know its history to understand its current dynamical state."*[1]
>
> \- Manuel DeLanda

Throughout history, innovations have been intrinsically linked to significant points of major and rapid advancements in civilization. Radical innovation occurs in many fields and paradigms, and not all of them are intrinsically technical; however, tools and other synthetic constructs are often catalysts for the abstraction of problems, for the changing of viewpoints, or for the suspension of disbelief, such that creativity can occur and reveal the potentials of new understanding.

Revolutionary points of bifurcation in industrial and architectural history are typically associated with advances in fundamental knowledge. Graphing historical industrial productivity against time readily identifies such inflection points. Innovations are revealed by inflections in the productivity or may be inferred from adjusted measures of prosperity.

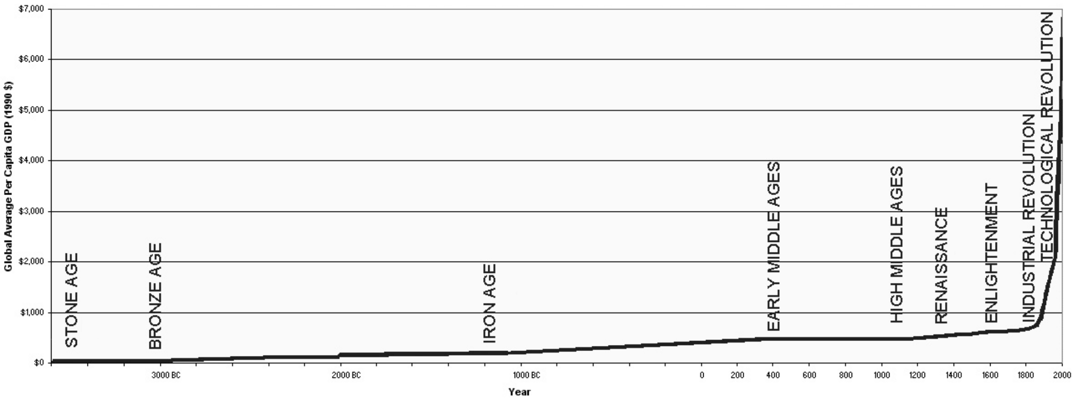


Fig. 2.1.1.a: Historical productivity: Global average per capita income (inferred) vs. year. Inflection points identify technical and productivity "revolutions". (Source: The World Economy: Historical Statistics, OECD)

The typical evolution of a known technology when graphed is a slow arcing curve, as its future development is dependant upon known consistencies and current understanding. Without any significant innovation, the expected path of evolution for that particular industry should be constant, eventually reaching equilibrium once all potential for refinement is exhausted. When a new significant invention is introduced into any process, the expectations of that industry suddenly change; making the representational graph non-linear.

An invention that significantly changes industrial and societal capabilities is a *bifurcation* in the evolution of that discipline. A bifurcation on the graph is a splitting of the path, with the "early adopter" portion of the graphed population following the revolutionary paradigm, and the remaining population remaining true to the existing state. A bifurcation marks a point, or an event at which a system divides into two alternative behaviours, and indicates a radical change to a phenomenon. If the bifurcation is *disruptive* enough the new mode of activity can prove to be a fundamental change to the industrialized state of a civilization.

---

[1] DeLanda M. " *A Thousand Years of Nonlinear History*":p.14

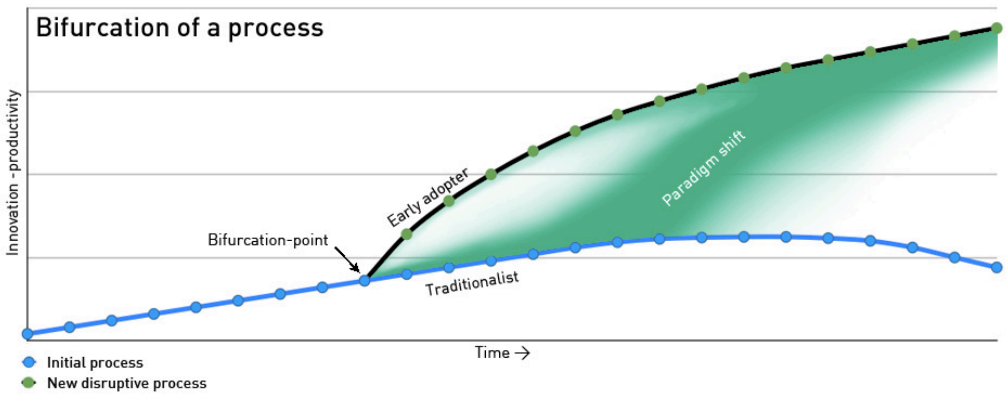


Fig. 2.1.1.b: Bifurcation of a process. Showing "S-curve" adoption profile of a paradigm-shift.

Acknowledged bifurcations in the development of human civilization include known ages and revolutions, such as the Iron Age, the Industrial Revolution, or the Information age.[i]

For each significant historical change in design, production, or industrial capability, it is possible to identify specific motivators of that change. These *stimuli* may be societal, cultural, economic, or dire necessity (such as production advances in a time of war), or the stimuli may be more noble factors such as inquisitiveness and enlightenment. Stimuli that occur at the intensity required to affect an entire system are considered to be *attractors*; parameters that cascade influences and effects on multiple factors such that they initiate wide scale change.

> *"Attractors and bifurcations are features of any system in which the dynamics are not only far from equilibrium but are also non-linear, that is, in which there are strong mutual interactions (or feedback) between components…"*[2]

Historically, bifurcation points are only identified retroactively. Through investigation, analysis and extensive modelling, researchers develop indicators to determine historical levels of productivity, and consequently identify key points of technical and cognitive development. The ability to detect bifurcations at this abstract scale is directly related to the precision and availability of statistical and historical information. As the datum timeline approaches the present, the quality, precision, and availability of recorded data increases, providing correspondingly better insight into the contemporary innovation productivity curve.

2.1.2. Paradigms

Paradigms are distinct philosophical and theoretical frameworks or epistemological contexts within which theories, laws, and generalizations can be formulated. The original Greek term *paradeigmata* was expressed by Plato, as the model or the pattern used in the field of *rhetoric*, as a term for an illustrative parable or representation of an idea.[3] As such, paradigms may be defined as the theoretical construct of rules and assumed conditions within which a concept or method can exist. Paradigms, as such, are an important basis for the acts of supposition, hypothesis, invention, and design.

The science historian Thomas Kuhn gave *paradigm* its contemporary meaning, but limited the use of "paradigm" to a list of objective investigations:

- What phenomena is to be observed and scrutinized
- The kind of questions to be asked in relation to this subject
- The structure of the questions
- What equipment is available to enable experimentation and questioning
- How the results should be interpreted

---

[2] DeLanda M. " A Thousand Years of Nonlinear History": p.18

[3] *Discussion with Socrates*: Argument 4. (132c-133a), in: *Parmenides*. Plato. Ref: Turnbull, R. (1998)

"*A paradigm is what members of a scientific community, and they alone, share.*"[4] Scientific knowledge is dependent on, and interconnected with the specific paradigm of its time. In this sense the prevailing paradigm represents a precise and specific way of viewing reality, and insomuch it has an effect of limiting the acceptable programs or methods for future research.

Paradigm is also used in unscientific contexts to describe patterns or typologically clear models. Used in this sense, a *paradigm* or *archetype* represents the functional genotype for a design instance, a model that includes opportunity for variability. This definition holds true for its use in digital theory, as a conceptual proto-programme used for managing complexity.

To define the meaning of paradigm in this thesis is important for two reasons: First, it is an acknowledgement that the word has multiple meanings, and that clarity is required to determine whether it is being used to describe thought, model, or context. Secondly, if a significant change occurs that affects the understood paradigm, then in all cases there is a required "re-orientation" of understanding. With this re-orientation comes a revision of methods, components, theories, and correspondently of design; this is called a *paradigm-shift*.

2.1.2.1. Paradigm-shift

Within the general scientific method, there is an inherent and predefined allowance for *paradigm-shift*. Understanding of our world changes through the process of discovery, and as this occurs, the inadequacy of an existing paradigm is revealed. When enough significant anomalies have accrued against a current paradigm, it is thrown into a state of *crisis* and the paradigm must be re-evaluated and changed.

"Successive transition from one paradigm to another via revolution is the usual developmental pattern of mature science."[5]

When paradigm-shifts do occur, they can be minor or extreme, however they tend to be most radical in contexts and systems that appear to have achieved maturity. The most common characteristic of such a paradigm-shift is the typical resistance of the populace (explaining why a paradigm-shift most often lags a bifurcation; *see: Fig 2.1.1.b*). Rather than a unitary inflection point, there is always a range of acceptance and rejection of a new innovation. The typical adoption profile of a paradigm-shift follows an "S-curve"; a graphed function that is a common pattern in most complex phenomena (physics, biology, economics, industry…).

The S-curve denotes the instigation, development, advancement, maturation, and eventual fall-off in both the development and adoption of a system: Early stages of process development are characterized by significant effort and resource expenditure but with only small-observed improvement. As inherent knowledge about the technology accumulates, progress increases; it is at this point that innovation may be radical. As soon as major technical obstacles are overcome, an exponential growth will take place. During this phase relatively small increments of effort and resources will result in large performance gains; it is in this time that most adoption and acceptance will occur. Finally, as the process approaches its physical limit, further improvement to the process or technology becomes increasingly difficult as the opportunities for improvement are exhausted.

The S-curve also typifies the adoption patterns. Initially a new technology attracts only "early adopters". As a technology becomes more robust and capable, adoption rates increase until a critical mass makes the shift. As the technology matures and innovation becomes more difficult the adoption rates achieve equilibrium, and then drops off.

Scientists proposing new paradigms are also subject to this S-curve in that they are often subject to (objectively justifiable) intense professional criticism and scrutiny. Physicist Max Planck summed up this resistance; *"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents*

[4] Kuhn, T.S.(1977) "*The Essential Tension: Selected Studies in Scientific Tradition and Change*": p.294

[5] Kuhn, T.S. (1996) "The Structure of Scientific Revolutions":p.12

eventually die, and a new generation grows up that is familiar with it"[6] The validity of a paradigm is not based on fact or truth, but rather it only comes to pass once there is a mass migration and acceptance of the paradigm by the immediately affected community.

Any radical innovation will affect its paradigm*, h*owever, the concepts and technologies, which allow change to happen may not be wholly responsible for that change. It is rather the critical and *mass acceptance* of a new paradigm that establishes a paradigm-shift. As such a new paradigm finds its root in both the objective issues of scientific promise and logic; but also in the subjective sociology of *rhetoric*, and design.

2.1.2.2. Polysemic paradigms

Once a paradigm is accepted as "true", the formal sciences cannot reject it without fundamental proof of incongruity or change. However in different disciplines, paradigms have varying levels of consequence. The existence of an anomaly in a paradigm is either an acknowledgement of its imperfection (initiating of further investigation), or may indicate that the possibility of *multiple interpretations* can be formally included in the paradigm.

In fields of investigation where techniques are abstract by necessity (for example: psychology), an investigator may choose to adopt an array of different *positions* as part of an analysis method. The use of *multi-paradigmatic potential* in fields such as the humanities (including subjective fields of research, such as design) is legitimate due to approaches required to investigate "that which is by its nature objectively unquantifiable."

Unlike normal scientists, Kuhn held, "*a student in the humanities has constantly before him a number of competing and incommensurable solutions to these problems; solutions that he must ultimately examine for himself.*"[7] In fields of investigation where there is an objective approach, but also an inherent impossibility of objectively proving a paradigm, the field is considered to be polysemic.[ii]

Many polysemic fields of investigation exist, particularly in more rationally abstract fields such as sociology, anthropology, psychology, and political science. In these investigations a "suspension of the truth" is objectively permitted in exchange for the promise of insight into the improvable. Although this approach defies positivistic and strict interpretations of the *scientific method*, it does allow for supposition, hypothesis, and potential innovation to work in non-linear methods.

Design, as a research field is polysemic, as there are many acceptable paradigms for design approaches and no single method is objectively correct (or incorrect). With this said, however, key parts of every design do have paradigmatic requirements (ex: physics, geometric composition, materiality, ergonomics and functionality…). For a design to achieve a critical acceptance it must respect, challenge, and yet still address the paradigms that constrain it, while simultaneously identifying those issues that are not paradigmatic. There can be no deliberate ignorance of facts, even when "thinking outside of the box".

A paradigm provides a consistent and simplified basis for reasoning: analogically this is "the box". "Thinking outside the box" is what Kuhn calls revolutionary science. Revolutionary science is usually unsuccessful, but very rarely it does leads to new insight, and subsequent large scale changes in the world-view.[iii] When a majority accepts a *paradigm-shift,* the new paradigm becomes "the box" and typically thereafter, iterative development will then progress within it.

2.1.3. Innovation

Any designed phenomenon (abstractly) consists of components, and the forces, linkages, and relationships between those components. In the fields of technology, the structural, organizational, logistical, and operational composition of a phenomenon (design, product, system or process) are referred to compositely as its *architecture.*[iv] Innovation as a process is

---

[6] Quoted from Max Plank in: McNeill, D., and P. Freiberger (1993):p.60

[7] Kuhn, T.S. (1996) *The Structure of Scientific Revolutions:p.165*

categorized as either incremental or radical, and the difference between the two types is identified based on changes to the components, the relationships, or the entire *architecture* of the phenomenon.

2.1.3.1. Incremental innovation

Incremental innovation modifies and extends an established design, but the underlying *architecture* is consistent. Incremental design (as a process) holds less risk, exploits existing knowledge, and is relatively efficient for value. Although incremental innovation creates no dramatically new design, it requires skill, ingenuity, and an awareness of the original design and changing contextual factors; be they new styles, new requirements, or the availability of new technology.

2.1.3.2. Radical innovation

Radical innovation, in contrast, is based on fundamental changes to the *architecture* of the design or process principles, and is often the product of a "re-visioning" of the problem at hand.[8] If widely accepted, radical innovation can cause a paradigm-shift, which poses difficulty for practitioners who are heavily invested in established methods or systems. Because this type of innovation fundamentally changes perceptions of process or product, and this often opens up new markets and potential applications, radical innovations are clear examples of *disruptive technologies*.[9]

Disruptive technologies are innovations (radical or iterative) that challenge their existing technical context. Although the innovation itself may not be radical, the introduction of the new technology is enough to *motivate* change in other products and application methods. *Disruptive innovations* do not invalidate existing design (the way that radical innovations do), but they do cause re-evaluation of the technical or business context. Radical and iterative innovation, have such different competitive consequences because they deal with information differently. Incremental innovation does not change the *architecture* of a design significantly from one step to the next, whereas radical innovation will completely redefine it.

The distinction between radical and incremental innovation produces important insights into how an individual or a society should respond to them. Understanding innovation types and their impact allows for the development of strategies that ensure that a product, method, or profession remain credible and relevant. However, for design and technology the simple application of this knowledge is typically inadequate. Within both design and technology, innovations that involve apparently modest changes to exiting technology can still have dramatic competitive consequences.[10] Within architecture it is becoming increasingly clear that it is the complexity and interrelatedness of technologies and techniques that affect the "larger picture" of implications, and not single inventions, applied in isolation.

2.1.3.3. Dominant design

Design and production are fundamentally concerned with the creation, manipulation, and communication of knowledge and information. Two concepts are important in understanding how component and relationship knowledge are managed:

The first concept is that process knowledge is built up through an iterative processing of tasks. Through iteration, designers acquire knowledge about the design problem, their own design response, and the relationships therein. This additional knowledge can be used to develop the solution, or "re-frame" the original design problem.[11]

The second concept is that of *dominant design*, the understanding that designs, methods, and technologies do not emerge fully developed from the designers desk, but rather that

[8] Dess and Beard, (1984); Dewar and Dutton, (1986).

[9] Christensen, C.M. (2003) *The Innovator's Solution*

[10] Clark, (1987): p.34

[11] See: Schoen, D.A. (1982) p.63.

the ensuing production and implementation processes also causes some degree of technical evolution characterized by experimentation, refinement and development. When a design, method, or technology has achieved a level of enhanced maturity and robustness, followed by a collaborative acceptance, it can be said to have achieved a state of *dominant design*.[12] A *dominant design* is characterized by a set of core design concepts and by an architecture that defines the ways in which these concepts are integrated.[13]

Iterative innovation occurs in the path to achieving the equilibrium of *dominant design*. Radical innovations, conversely, have the potential to destroy the *dominant design* of established processes and knowledge. Given that knowledge, methodologies, and styles tend to become embedded in practice (*dominant design* methods), new technologies and methods can be perceived as a threat to existing firms and their traditions of practice.

2.1.3.4. Implications

At the onset of radical innovation, there is little agreement about how best to apply, accommodate, and implement new technologies; and there are few "experts" from which to gain this knowledge. This *disruption* creates the two possible paths of a *bifurcation*.

One path is the rejection of the new paradigm and uncertainty that accompanies it. This "safe" path proscribes the continuation of the known technologies and the *dominant design,* but it also means that the room for continual improvement of knowledge, process, and product is limited and already heading for obsolescence.

The second path is to embrace the new technology, and accept the challenges that accompany it. This path instigates a necessity for experimentation, often at the cost of productivity[14], but also often to the benefit of creativity, expression, and design innovation. The outcomes of such periods of innovation can be seen in schematic early work emerging from avant-garde schools, young technocratic design firms, and innovation offices (where commercial productivity is, perhaps, a secondary concern).

Paradigm-shifting technologies, through their very popularity and acceptance do eventually become "normal", and their novelty becomes commonplace. This maturation comes through next step iterative refinement, and the development of knowledge and deep understanding. Originality is brought to an end by the emergence of the next *dominant design* for the technology and its related methodologies.[15]

2.1.3.5. Advantages

It is important to state here that neither iterative nor radical innovation is "better" than the other. Radical innovation has significant competitive implications, but also costs. Established methods and iterative approaches to design (acknowledging the existing paradigms) are equally valid in polysemic fields such as architecture.

There are significant reasons for choosing either path at a bifurcation point, and the choice may be dependant on factors outside of either design or technology (such as economics, conservative markets, or client preference…); however this thesis investigation is concerned with the effects of technology on the practice of architecture, thusly understanding the effects and risks of innovation is the main goal of investigation.

New technologies, tools, and processes will not (on their own) invoke radical change of existing methods. Without an understanding of the reasons for change, the benefits of any new technology for practice are unlikely to produce innovation in design. Design innovation comes from complex interactions of factors that affect the problem definition, the tools for solving it, and the knowledge and skills of the practitioner. This thesis seeks to investigate these factors to determine how to foster creative innovation in a technologically mediated architectural practice.

---

[12] Mansfield (1977), Clark (1985), and Sahal (1986)

[13] Henderson and Clark (1990): p.12

[14] Burns and Stalker (1966); Clark (1985)

[15] Sahal, D. (1986) : p.63.

2.1.4. Future adaptability

In *Technology and Change,*[16] the central argument of Professor Donald Schoen is that change is a fundamental feature of modern life, and that for an individual to prosper it is necessary to develop methods and systems that can learn, adapt, and evolve.

> *"The dilemma of the professional today lies in the fact that both ends of the gap he is expected to bridge within his profession are changing so rapidly: the body of knowledge that he must use, and the expectations of the society that he must serve. Both these changes have their origin in the same common factor: technological change … The problem cannot be usefully phrased in terms of too much technology. Rather it is whether we can generate technological change fast enough to meet expectations and demands that technology itself has generated. … This places on the professional a requirement for adaptability that is unprecedented."*[17]

Here, adaptability is intrinsically related to the issue of the technological bifurcation. As a paradigm changes there is a resistance to "the new" by those who have invested heavily in traditional methods. However, with design being polysemic, there is no "correct" choice to be made, both new and old are conceptually valid. What is clear however is that it is intrinsic upon the professional to understand the implications of their choice.

> *"Ostensibly a contemporary technique's contribution lies in the progress of a culture driven by a mechanic process which self-organizes, bifurcates, and produces new emergent results."*[18]

This thesis seeks to explore the implications of digital technologies on the profession, practice, and teaching of architecture. The specific approach of the thesis is to explore new tools, concepts, and methods of digital architecture with the goal of understanding the current state of practice. The overall goal is to expound this current position so as to strategize for future development, and achieve a critically informed position on issues of digital adaptability.

2.2. Thesis Investigation

> *"Over the past fifteen years, architecture has been profoundly altered by the advent of computation and information technology. Design software and numerical fabrication machinery have recast the traditional role of geometry in architecture and opened it up to the wondrous possibilities afforded by topology, parametric surface design and other areas of mathematics. … the impact of computation on the discipline has been widely documented."*[19]
>
> - George Legendre

There is no denying that digital tools are having a profound effect on how design is now conceived, formulated, developed and produced. The digital medium offers tools and capabilities that were unknown in traditional media, including advanced methods of organization, fast manipulation of geometry, and the computational simulation of design conditions. These advances in productivity have had substantial effect on both the work, and working conditions within the practice of architecture, a profession not known for early adoption of radical innovation. Digital tools and the use of the computer as a working medium have been shown to be a *disruptive technology* in their use as a platform for undertaking organizational, clerical, and text based professions[20]. However, other more technologically complex capabilities, such as explicit computation, simulation, evaluation, and optimized production have already been developed for design in other similar fields, and yet remain underutilized in architectural processes.

---

[16] Schön, D, A. (1967)

[17] Schön (1982):15. H. Brooks: "The Dilemmas of Engineering Education". In: *IEEE Spectrum* (Feb 1967):89.

[18] Rahim, A. (2002):p.5

[19] Legendre, G. (2011)

[20] Christensen, C.M. (1997)

In 1965, at the origins of design computation, Christopher Alexander rejected the use of computers, comparing them to unintelligent tools: *"A digital computer is, essentially, the same as a huge army of clerks, equipped with rule books, pencil and paper, all stupid and entirely without initiative but able to follow exactly millions of precisely defined operations."*[21]

The popularization of the personal computer and digital design software enabled academics, researchers, and "avant-garde" practitioners to investigate digitally mediated architecture. As digital design and numerically controlled fabrication approach a greater degree of maturity, and widespread deployment, the technologies have produced significant examples of innovative applications and expressive design, exploring issues of both theory and practice. However, in the associated literature, both academic and professional, there is still a wide divergence of opinions as to what degree of impact these new technologies have had.

Some proponents[22] take the view that the combination of the computer, digital design software and the resulting digital methodologies constitute a radical innovation of both theory and practice: A paradigm-shift in architecture. More moderate, but biased technocratic practitioners are proposing a "*Parametricist Manifesto*", and claim that the technology is at the root of a new *mature style*.[23] Other, more pragmatic critics, still hold with the original statement of Alexander, that these technologies are but an iterative innovation; the application of new tools to the traditional architectural paradigm.[24]

The fact that these contradictory positions meander between radical criticism, scepticism and wholehearted acceptance and yet coexist simultaneously is the instigating point for this work.

2.2.1. Thesis statement

This doctorate research will examine the on-going implementation of digital technologies in the discipline of architecture, with specific investigation of technology as an evolutionary motivator in the processes of design and production. The principal question to be resolved for this thesis is:

> *Does the current implementation of digital tools and computational power constitute a paradigm-shift in the field of architectural design and production?*

The thesis questions whether the digital chain, and specifically digitally driven design and production, is an evolutionary bifurcation point in the architectural process. If the answer is positive, then do new technologies constitute a new *paradigm* in architecture, or have innovations only been iterative to this point?

2.2.2. Purpose

> *"…and architects will have to function in radically new ways as a consequence of the introduction of new building technologies, new patterns of real estate and land development, and new techniques of information processing in design. As the tasks change, so will change the demands for usable knowledge, and the patterns of task and knowledge are inherently unstable."*[25]

The objective of the investigation is to position current technologies, and to clarify conceptual ambiguities primarily caused by the lack of relationship between practice and an overall architectural theory when dealing with advanced digital technologies. This thesis may therefore be considered a critical reflection and theory development, rather than a traditional historical research or technical proof.

The main intention of the thesis is to explore the current architectural-technological paradigm so as to understand if technology represents *iterative* or a *radical* innovation.

---

[21] Alexander, C. (1965)

[22] Lynn, G. (1998); Mitchell, W.J. (1999); Arayici, Y. et al. (2010)…

[23] Schumacher, P. (2008)

[24] Frazer, J. (1995); Meredith, M. (2009)

[25] Schön (1982):15

Although this goal may appear to be somewhat semantic, this understanding has significant strategic consequences for the future development of the profession and its use of technology.

In the case that the current use of digital tools in architectural design and production does not constitute a *paradigm-shift*; that digital technologies represent an *evolution* of practice and a form of *iterative* innovation; then the findings will be essential to understand potentials for future developments of praxis, and the potentials for further *radical* change.

In the case that methodologies and concepts have already been *radically* changed, then an understanding of the affects of such change is required. If acknowledging that a *paradigm-shift* has occurred, then (by default) there is a specific requirement that practitioners address their own working "assumptions" and proceed in radically evolved way. If digital technologies have indeed changed the paradigm of architecture, then the profession is already on a path of development with these technologies that is irrefutable, and new methods for working, producing and teaching architecture need to be implemented that address this new paradigm.

However, a third possibility also exists. If a bifurcation of architectural production has occurred – meaning that we accept digital technologies as being *disruptive technologies*, but if the practicing mass has yet to adopt their *radical* nature, then the fundamental questions become: "*What confluence of factors will need to coalesce before there is a fundamentally radical change?*" and, "*In our current understanding and context is this radical change likely, possible, or even desirable?*"

By developing an overview and taking a position on the current state of technology in architecture, this thesis seeks to make critically informed predictions that will help direct technological change such that it is beneficial to creativity and expression in design. In knowing whether a paradigm-shift has occurred, or, if it is likely to occur, the contemporary practitioner and academic will be better prepared for future technologies, and can be suitably positioned to capitalize on innovations as they occur.

2.2.3. Approach

Architecture and technology are both inherently intricate, and investigating this complexity is the first step in the approach to this investigation.

To deal with such complexity it would be tempting to abstract and simplify the issues such that they can be contained and developed in a linear and analytical manner. However because of the *holistic* and *systems* nature of the chosen topics, such abstraction results in a reduced and potentially superficial understanding. It is the complexity of interaction between the fields of design and technology that is of primary interest in this investigation. Many (seemingly) minor parameters in these fields are still very influential in both the acceptance of technology, and the act of innovation in architectural process. As such, efforts have been made to reveal the high degree of interconnectedness between theoretical concepts in the thesis narrative. To do this the thesis will investigate the individual issues of history, theory, and philosophy that affect both architecture and technology. The epistemological development of the research is based on comprehensive reviews and analysis of publications.

The contextual understanding of technology and architecture is complimented by practical investigations. Architectural design and production projects were conceived to investigate the issues of tools and skill development, but also to gain an overview of methodology and the issues that affect professional adoption of technology. A fundamental question that was repeatedly addressed in the practical investigations was how to rectify the perceived disjoint between the subjective and creative approach to design, and the highly objective and logical medium of digital tools.

Creativity is expressed in the content of design decisions, but also in the hierarchical development of the project. If a design is viewed as a methodological process, then a project that is developed "digitally" will be influenced by how the designer works the design, but also by the development medium of the chosen technologies. When a project is developed using computation and programming, then the constraints and restrictions of such a logical, rational, and objective medium also have a fundamental affect on the results. This question of “creativity in a medium of rational tools”, is the basis for the practical investigations.

By undertaking focused projects using advanced digital design and production technologies, and by deriving conclusions based on practical experience, the investigators gained insight into the linkages between architectural theory and practice, and how they can still creatively be manipulated using computational technology.

The research portion of the thesis concluded by integrating the, findings from both the practical and theoretical investigations in a discussion of future potentials for emerging technologies in architecture.

2.2.4. Results

The conclusions of the thesis return to architectural theory and practice by relating the findings from the practical investigations to the ideological research.

One result from this doctoral work was to verify the hypothesis that typical architectural design strategies have a strong structural and methodological similarity to computer programming methods. In exposing this similarity, there is significant advantage for further optimization of both design content hierarchies and the overall design process development.

This thesis purports that *digital tools* and the *digital medium* are *disruptive technologies* and that they do implicate a bifurcation point in the architectural productivity. However the main question of whether there has been a corresponding *paradigm shift*, and how the current approach to technology should evolve, is less clear. This topic is taken up in the discussions, by showing predictive strategies for the development of digital design and production, and relating them to architectural practice.

2.2.5. Significance

The potential value of this thesis results is not a specific technology or theory, but it is rather an overview of the current relationship between architecture and technology. Results from this doctorate work demonstrate how design and production have evolved through the use of digital tools, and state whether the current strategies are taking full advantage of the computational medium.

The conclusions of this investigation have significance in informing the refinement and optimization of architectural design, production, and teaching methods. Through this investigation and the understanding of the complexity of interrelated issues, it has been possible to identify and develop strategies to accommodate change in such a multifaceted profession.

Both architecture and technology are in a persistent state of change, and an academically credible study of their influence should establish a solid basis for future architectural research. By qualifying methods that aid in predicting technological advances in society and civilization this thesis should provide a platform for creative and inspired technological synthesis. Having insight into the factors affecting future potentials in architecture has significant value.

The goal of both the research and the practical investigations is to allow for progressive evaluations and conclusions about the digitally mediated processes and their affect on the architectural paradigm. Each node in the knowledge network that makes up this research reveals how the concept of the *information machine* can be used to manage complexity. With this broader understanding the research, should allow for an informed assessment of the future of digital technologies and the digital chain in architecture.

2.3. Foundations

> *"No person who is not a great sculptor or painter can be an architect. If he is not a sculptor or painter, he can only be a builder."*
>
> \- John Ruskin

Architecture as a discipline is a true merging of subjective artistry and objective reasoning. These two sides are perpetually in flux and highly variable from one project and one author to another. The nature of design, however, requires the practitioner to address both of these traits simultaneously so as to find an appropriate balance for each design. That such emphasis is placed on the subjective skills of a designer finds a contradiction to the increasing importance of logic and empirical values in society.

If the act of design is entrenched in subjective expression, and at the same time the tools and methods being employed are becoming increasingly more rational and objective, is there not a risk of this inconsistency affects the future potential of the profession?

2.3.1. Motivations

> *"We know that only the technical means of artistic achievement can be taught, not art itself. The function of art in the past has been given a formal importance that has severed it from our daily life: but art is always present when a people live sincerely and healthily. Our job is therefore to invent a new system of education that may lead - by way of a new kind of specialised teaching of science and technology - to a complete knowledge of human needs and a universal awareness of them. Thus our task is to make a new kind of artist, a creator capable of understanding every kind of need: not because he is a prodigy, but because he knows how to approach human needs according to a precise method. We wish to make him conscious of his creative power, not scared of new facts, and independent of formulas in his own work."*[26]
>
> \- Walter Gropius

The primary motivation for the thesis is to support the idea that artistry, creativity, and innovation can coexist, and thrive with (or despite) the use of objective and technologically derived processes and tools. This position echoes the 1919 prospectus for the Bauhaus design school, which states that artistry is developed and fostered, but not actually taught. Gropius's declaration states that excellence and appropriateness in design emerges in a context of knowledge and skill building, but also through expanding awareness of other disciplines and scientific and social issues. This thesis is sympathetic to this approach.

The investigators motivation to reinforce the coexistence of technology and its symbiosis with design is supported by a longstanding personal engagement of technology in the practice of architecture. This section presents three topics that set the theoretical and historical context for these issues. These topics are presented to substantiate the personal motivations in a theoretical context, and to practically ground the theory as context for the thesis argument.

Rationalism, and the increasingly dominant role of empirical evaluation and tools in design are presented to show how architecture and other subjective crafts increasingly need to justify their design decisions based on objective merit.

Rhetoric, as both a historical concept and a process was researched to understand its position between logic and artistry, and how it relates to the contemporary practice of design.

The final contextual study of this section investigates how architecture and design have evolved with respect to empirical technologies, and the understanding of what criteria now determine how new technologies are implemented into design methodologies.

These three issues have been researched and are presented here in essays form, so as to provide a foundation for the further epistemological work of the thesis.

---

[26] Gropius, W. (1919): Statement from the prospectus for the Bauhaus design education in Weimar.

2.4. Rationalism and architecture

> *"… we must radically rethink the goals, context, and technology of the computer and all the other technology crowding into our lives. Calmness is a fundamental challenge for all technological design of the next fifty years."*[27]
>
> \- Mark Weiser and John Seely Brown

Since the Enlightenment, the rise of science and technology in civilization has been both cause, and consequence, of a rationalist world-view. As these doctrines slowly permeated Europe, the adoption of empiricism and rational thought in the learned class led to the creation of the first societies and academies and the maturation of the scientific professions. By the end of the 18th century, scientific authority began to displace religious authority, the disciplines of *alchemy, astrology*, and *theurgy* lost credibility, and with its historical basis in Aristotle's "*Analytics*", the hypothetico-deductive model of logical reasoning was formalised into what is now called the Scientific Method.

Rationalism, represents the view that any "reality" is objective, measurable, and can be described through the application logic.[28] According to rationalist views, there are three progressive levels to professional knowledge: The application of *basic science* to a problem yields *applied science*; the application of *applied science* to a problem yields *diagnostics* and *experience*. Applied science is said to rest on "basic" science, and that the "first principals" lead to the possibility of diagnosing a problem and providing a solution.

Once empirically described, any information allows for the prediction of phenomena. It is within this issue of prediction that rationalism has its value. The constituents of technical rationalism are empirical observation, verification, repeatability, and deduction. These methods of inquiry (as defined by Newton[29]) have remained the dominant epistemological method in both professional disciplines and academics since their modern re-emergence.

As the sciences were formalized, the significant discoveries manifested themselves as new scientific understanding in mechanics, power, and control devices. These innovations directly enabled the powering of industrial mechanisms, and the start of the industrial revolution.

2.4.1. The rise of professionals

Although this technological paradigm-shift had great negative implications for employment in the worker class, it did foster a new class of worker: the technician. As the industrial and economic potentials of these innovations became clear, technicians were drafted into the fields of investigation, mechanistic refinement, and eventually into invention. The required technical skills were augmented with empirical methods, and the top technical workers transformed into the role of the "applied scientists": Engineers.

As part of this transformation, the adoption of scientific rigor in machine development resulted in both improved of practical knowledge, and significant industrial (and economic) successes. Expert practitioners solved well-formed instrumental problems by applying theory and technique derived from systematic (and preferably scientific) knowledge. Soon thereafter, "professional practice" became a prototype for most technical or science based professions, and the combination of practical skills and a strict application of logic, methods and rules, became a template of practice for other disciplines, such as medicine, law, and accountancy.

With the progression of industrialism in western culture, the triumphs of science and technology overshadowed the "irrational" residues of mysticism, metaphysics, and to some degrees even religion. However, the dominance of objective reasoning also resulted in the devaluation of craft, artistry, and most issues that were determined to be subjective in nature.

---

[27] Weiser, M., Seely Brown, J. (1996)

[28] Papell, C., & Skolnik, L. (1992)

[29] In: Newton. Book 3 "*The System of the World*" of his *Rules for the study of natural philosophy*

"Against the rigorous perfection of the machine, craft became a representation of individuality, with nostalgic value placed on the irregularities of handwork."[30] This undermining of creativity and artistry was bemoaned by figures such as John Ruskin, who wrote of a romantic resistance to capitalism, machines, and his promotion of a return to pre-industrialized age of craftsmanship. "*Life without industry is guilt. Industry without art is brutality.*"[31]

Although Ruskin is highly regarded for his contributions to the arts and society, his opinions, proposals and philosophies could not compete with industrialism and the changes it brought forth. As the industrial scientific paradigm gained dominance it resultantly also influenced development of economics, politics, social issues, and education.

2.4.2. The rise of the rationalist institution

The emergence of American universities in the late nineteenth coincided with the influence of rationalism. The migration of academics from European institutions reinforced the rationalist doctrine with Germanic and English traditions of empirical investigation, while the success of medical and engineering models exerted great influence on other disciplines.[32] Social studies became social sciences, politics became political science, and the application of rigorous empirical methods to studies of the humanities became rich with references to measurement, controlled experiments, and statistical analysis. The coincidences of these developments set the paradigm for research and education in higher education, one that remains to this day.

> *"Technical rationality is an epistemology of practice derived from positivist philosophy, built into the very foundations of the modern research university."*[33]

As education and the professions evolved, this doctrine shifted to industry with the advent of "industrial engineering". As industry evolved, mass production and consumerism created a profit driven amplification loop, reinforcing rationalism within society. However, it was the scientific study of efficiency methods in the workplace that brought technical rationalism to the individual working man.

2.4.3. Industrial optimization

In the 1880's, Frederick Winslow Taylor, an American mechanical engineer, developed tests to measure the efficiency of human workers. These tests recorded movements, time intervals, and individual productivity so as to rationalize and standardize methods. The goal, was not necessarily to increase productivity, but rather it was to make overall production more consistent, and therefore and economically predictable.

> *"Taylorism is founded on six principles: The primary goal of human labour and thought is efficiency; that technical calculation is in all respects superior to human judgement; that in fact human judgement is plagued by laxity, ambiguity, and unnecessary complexity; that subjectivity is an obstacle to clear thinking; that which cannot be measured does not in fact exist or is of no value; and that affairs of citizens are best guided and conducted by experts."*[34]

Before the scientific analysis of working methods, individual labourers relied on experience, training, and heuristics to conduct their work; essentially writing their own "script" to determine the steps of a task. However, once advantages of efficient methodologies were demonstrated to the industrialists, Taylor would be given licence to develop strict sets of instructions for each of the tasks, positions, and jobs within the industry. These prescriptive sets of instructions, removed any subjectivity or interpretation from process. The worker followed a script written by someone else, and were not expected to understand how the script was constructed or the reasoning behind it. In this way the requirements of personal knowledge and expertise of process was eliminated, and the individual became replaceable.

---

[30] Sennet, R. (2010):84

[31] Attributed to John Ruskin, in Lecture III of his "Lectures on Art" (1870)

[32] Shils, E. (1978):164

[33] Shils, E. (1978):160

[34] Postman, N. (1993):.51

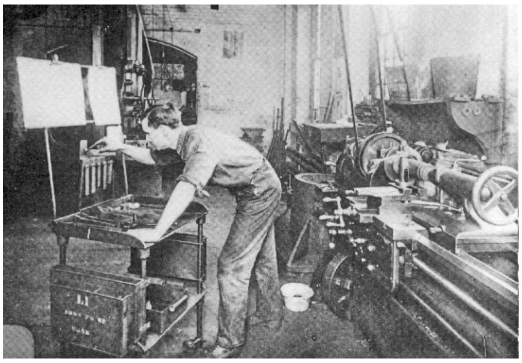
"By breaking down technical job into a sequence of small steps and ten testing different ways of performing them, he created a set of precise instructions – an algorithm for work."[35]

Even as workers complained that the strictness of applying the new methods reduced their work and roles down to little more than mindless automatons, their productivity improved and production became more predictable. These "successes" led to the adoption of Taylorist evaluations and methods in other industries, with Taylor declaring: *"in the past, man has been first, in the future the system must be first"*[36]. With this proclamation the Industrial Revolution found a philosophy to fit the rationalist and mechanistic application of technology.

The other leading figure of workflow efficiency analysis of this time is Frank Bunker Gilbreth. In contrast to Taylor, Gilbreth's research did not have, as its goal industrial profitability, but rather its focus was ergonomics and efficiency of movement.

"The symbol of Taylorism was the stopwatch; Taylor was primarily concerned with reducing process times. Gilbreth, on the other hand, sought to make processes more efficient by reducing the motions involved. He saw their approach as more concerned with workers' welfare than Taylorism, which workers themselves often perceived as primarily concerned with profit."[v]

Gilbreth developed methods for the ergonomic optimization of diverse activities. His methods included the adoption of innovative technologies such as high-speed cameras for motion studies (as pioneered by Eadweard Muybridge), calibrated to reveal the minute motions in workflow; he called this invention a *chronocyclegraph*[37]. His career and methods are credited with (amongst others) the idea of a surgical nurse as a surgeons "caddy", and with the development of the routine military techniques of how to rapidly disassemble and reassemble small arms and weapons.



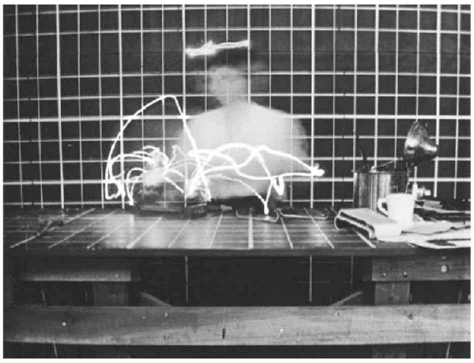


Fig.2.4.3. Work efficiency investigations: a.) Taylorist machine worker investigations; b.) Gilbreth, image based "chronocyclegraph" worker movement investigations.

The comprehension of industrial and worker efficiency radically evolved during the production booms of the first and second world wars. Increases in both the scale, complexity and productivity of wartime manufacturing was partially a result of the scientific investigations of Taylor and Gilbreth, but also of the manufacturing capability developed by industrialists such as Henry Ford, and innovations developed in Japanese–German industrial co-operation. The unprecedented need for technological supremacy at this time challenged, and eventually transformed expectations for manufacturing, scales of efficiency, and the capabilities of design and production.

[35] Carr, N. (2010):149

[36] Taylor, F.W. (1911)

[37] Hebeisen, W. (1999): 21

2.4.4. Post war industrial architecture

Manufacturing in post-war America shifted focus to the production of needed consumer goods. New products incorporated war-time manufacturing innovations, and the resulting consumer grade electronics, appliances, and the mass production of the automobile made technology ubiquitous in the homes and daily lives of the general public.

The war also caused significant change to society through the return of servicemen, the re-domestication of women industry workers, and the subsequent baby booms. The dramatic increases in demand for housing, education, and employment changed population demographics, and the increasing population further amplified this consumerism.

The existing infrastructure for mass production, established in wartime, combined with strong demand for both jobs and housing motivated the industrialization of architecture and the evolution of pre-fabricated housing. At one time over seventy housing factories existed in the USA[38], however the most memorable innovations occurred when creative architects employed sciences and techniques derived directly from wartime innovations. The "Dymaxion House" (1947) developed by Buckminster Fuller in collaboration with The Beech Aircraft Company, and the "Packaged House System" (1947-52) houses developed by Walter Gropius in collaboration with the General Panel Corporation, are two such examples.[39]

Fig 2.4.4. a.) The Dymaxion House II, 1947. Fuller Houses, Inc.; b.) Walter Gropius and Konrad Wachsmann, Packaged House System, 1947: General Panel Corp.

The creativity of the architects was both propelled and constrained by the very rational issues of the pre-fab housing model. The economics, transportation and the speed and ease of assembly required to make the systems functional and worthwhile were elusive, and the integration of any "non-standard" design elements was problematic and costly. Style, individuality, and responsiveness to context took a secondary position to the development of standardized material systems, flat packaging, and on-site construction optimisation.

> *"After the war there was a prefabricated housing boom in the United States. … Almost overnight, architects of the still young Modernist movement became enthusiastic about new building materials and what seemed like unlimited technological progress. Industrial production became a model, both in terms of material aesthetics, as well as production technology. The machine became a central metaphor of modernism. It dominated design practice of architects and designers to the smallest detail. It is no wonder that innovations in the field of industrial mass production piqued the interest of architects."*[40]

In Europe, where the need for housing was most dramatic, pre-fabricated housing was extensively deployed. However, the local population was reluctant to accept the architecture due to poor quality, shoddy construction, and the perceived lack of cultural sensitivity.[41]

---

[38] Gössel, et al. (2010):13.

[39] Gössel, et al. (2010): 72 +112.

[40] Gössel, et al. (2010): 14.

[41] Gössel, et al. (2010):21.

This negative attitude and these problems eventually transferred to North America. Even though this period was marked as a time of significant scientific and technological innovation (ex: the moon landings), prefabricated housing became typified by a series of conceptual "futuristic utopian lifestyle" prototypes, rather than a practical, normal, and socially desirable means for home construction. The market and perception of pre-fabricated housing systems has never recovered since.

Fig 2.4.4. c.) Monsanto House of the Future, 1957. Monsanto, MIT, and Walt Disney Imagineering.

2.4.5. Intellectual technology

As a parallel development to these advances in industrial productivity, the innovations from wartime in the fields of science and engineering were profound. The understanding of atomic power, the development of jets and rockets, the emergence of complex electronic circuits, and the development of the first electronic computers were all radical innovations that redefined civilization. The propagation of these technologies into academia came from post-war convergence of scientists and engineers at academic and governmental institutions in the western world. Their positions as teachers, researchers, and governmental consultants further amplified the rationalist doctrine and its position in societal reasoning.

Aside from the afore-mentioned issues of industrial architectural production, the most significant innovation of this time was (at least, for the purposes of this thesis) the development of the programmable electronic computation machine – the predecessor to the modern computer.

The ensuing evolution of the computer was driven by academic, scientific, militaristic, and governmental needs, up until the development of the integrated computer circuit in 1958. With this invention, the size, cost, and infrastructure for operating such machines trickled-down to the point that they could be implemented in universities, making possible an entirely new field of investigation: computer science.

By the 1960's computers (as "main frame" devices) were generally available at the larger institutional universities in the United States. It was at MIT in 1963 that Ivan Sutherland, as part of his PhD thesis, developed the first recognized Computer Aided Drafting program[42]. Using a light-pen on the interactive computer screen, it was possible to create data points which could be used to define geometrical "objects". Despite the ground-breaking shift of working medium, the most radical and impressive features of the program were related to the programming. The first invention was the ability to create "instances" of geometry; the first use of graphical and digital "cut, copy, and paste". The second major invention was the ability to *fix* or *constrain* geometric properties (ex: length of a line or angle between two lines). This feature made explicit the technological linking of "active" geometry, mathematics, and design, and today this basic principle is recognized as the root of algorithmic and parametric design.

---

[42] Sutherland, I (1963)

The development of Sketchpad and subsequent digital graphics systems, are not the first artistic use of computation, but they are significant in that their invention begins the discussion concerning technological constraints, and their impact on innovation on intuitive and artistic media.

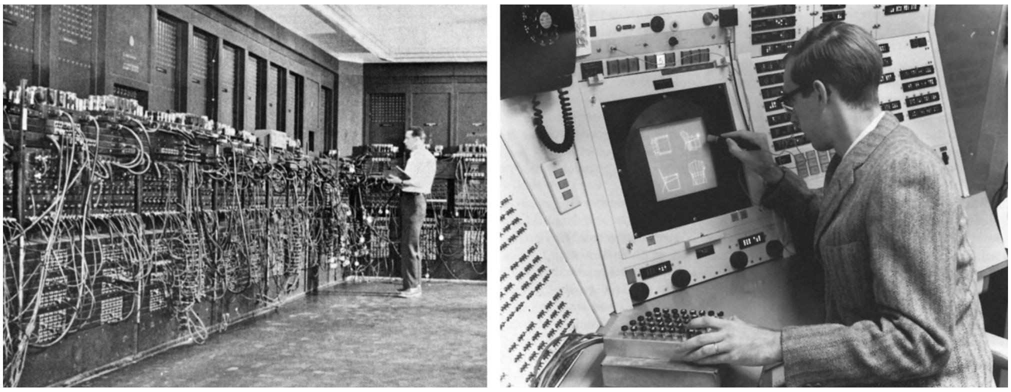


Fig. 2.4.5.a.) ENIAC, the first general purpose electronic computer, at University of Pennsylvania 1943; b.) Ivan Sutherland, Sketchpad program on the Lincoln TX-2 computer at MIT, 1963.

The contemporary development of the computer, and the progression of digital media, programming and the software are well documented (and will not be described here).[vi] Likewise, the history and evolution of architectural movements with respect to technology and culture are also well documented elsewhere.[vii]

2.4.6. Complexity in context

"*… but what started out as a liberating stream has turned into a deluge of chaos… for the average person, information no longer has any relation to the solution of problems.*" [43]

As technology and communications have evolved the quantity of available information in our daily context has dramatically increased. The complexity of any system is dependant upon its components and their interrelationships, as the ability to forge new linkages increases, so too does the complexity of the system. The complexity of the world is increasing, and the fact that technology is both cause and response presents a paradox for the architect.

As life becomes more complex, practitioners increasingly turn to the clarity of rationalism to aid in determining "a" solution, …if not the best solution.

The increasing complexity of our world is an on-going theme in architecture. Professor emeritus of the Architectural Association, Royston Landau stated, "*the ex-craftsman's designer is faced with a new, multi-variable world in which the old delineations of his activity are no longer applicable*."[44] With this Landau acknowledges changes in society coming from an "*accelerating growth of information and knowledge*". Landau explains that the architect, like all professionals, responds to increasing complexity through the use of tools and intellectual devices, creating great future potential for architectural computation.

The emergence of digital communications, the Internet, and digitally connected computers has amplified the growth of complexity, resulting in a radically redefined engagement of information systems to manage it. The American scientist and mathematician, Dr Warren Weaver, proposed in 1959 that the biggest challenge to the scientific community in the future, would be addressing problems at dramatically increasing scales of complexity. To qualify this statement Weaver developed a categorization of problem types, to show that as civilization evolves "it solves the easy problems first".

---

[43] From lecture: Postman, N. (1990) "Informing Ourselves to Death"

[44] Landau, R. (1968) :11

According to Dr Weaver there are three fundamental classes of problem:[45]

1. Problems of simplicity: These are the typical problems of the *enlightenment*, characterized as problems with a small and limited number of variables. These problems are typically solved using methods of abstraction and basic algebra. (Ex: 2 billiard balls, basic rules of physics, Newtonian problems, and simple one or two variable problems.)
2. *Problems of disorganized complexity*: Problems of this class feature multiple independent variables such that statistical analysis, and calculus are required to solve them. These are problems of simple systems where relationships between variables are limited (Ex: molecules of gas = pressure.) The model of such systems are easily abstracted and broken down for analysis, the components of the analysis are typically "problems of simplicity".
3. *Problems of organized complexity*: High complexity problems have multiple variables that have complex interdependencies. At the extreme of such problems are *wicked problems,* situations where both the context and relations between parameters are in a confounding state of change. This interrelatedness between variables is highly problematic to model and predict. (Ex: life-sciences, biology, or weather)

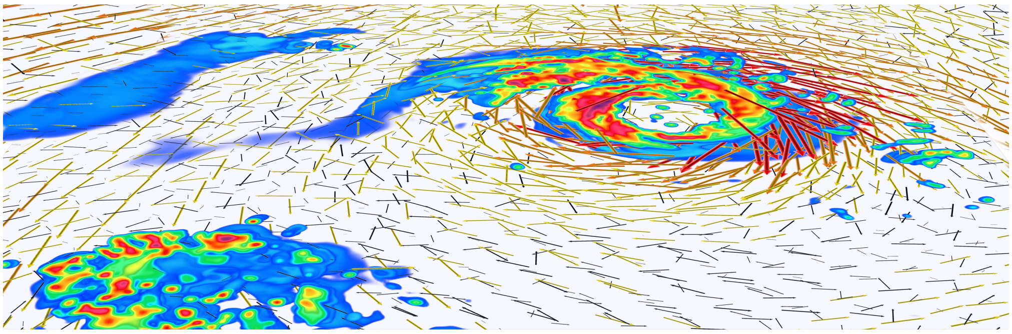


Fig.2.4.6. Simulation of organized complexity: Center for Analysis and Prediction of Storms, University of Oklahoma: Visualization: Pittsburgh Supercomputing Center, Carnegie Mellon University.

The current state of most computational devices and their programming is that they are able to deal with *problems of simplicity* and *problems of disorganized complexity*. Advanced "super-computers" with specialized programming are able to simulate and evaluate rational *problems of organized complexity* such as complex environmental and ecological systems. However, subjective problems *of organized complexity,* such as design synthesis, social opinion, or other significant humanistic issues are not solvable. These problems are termed "*wicked problems*".

Wicked problem are problems that are difficult to recognize, and may be impossible to solve because of incomplete, contradictory, and changing requirements. They have complex interdependencies, similar to organized complexity, however the changing state of parameters and changing state of relationships means that they are unstable; as such, the solving of one aspect of a wicked problem may reveal or even create other problems.[46]

Wicked problem have been defined as having several defining characteristics:

- The problem is not understood until after the formulation of a solution.
- Wicked problems have no stopping rule.
- Solutions to wicked problems are not right or wrong.
- Every wicked problem is essentially novel and unique.
- Every solution to a wicked problem is a 'one shot operation.'
- Wicked problems have no given alternative solutions.

Technology in the form of digital modelling and processing is increasingly being used to, first "tame" such wicked problem, and then once the model is contained and changing context and parameters are stable, the problem may be solved.

---

[45] Jacobs, J. (1961):429

[46] Rittel, W.J. and Webber, M.M. (1973):138

As technology makes it easier to create, measure, and report on phenomena, people are exposed to increasing amounts of available data. Data is provided from multiple sources, and as such it is conceivably subjective and opinionated in nature; correspondingly there is an increase in potential for conflicting or "ill-formed" information. The quantity of data is not the problem, but rather it is the divergence of "truths" and the resultant duty of decision that this places on individuals: Conflicting information invokes a state of "digital anxiety."[47]

"Digital anxiety" exists where, as more conflicting information is presented, there is an increased likelihood that that the user becomes cynical about information. However, if information is provided as an absolute truth, an *episteme,* then the root of cynicism is null.

Rational epistemological systems are fundamentally constructed for the purpose of creating absolute truths. So when a computer, a logic machine using empirical operating methods, provides a piece of data, a result, or a solution to a given problem, there is a propensity to regard that solution in a different mind-set than if it comes from an unknown source.[48]

Although historically there has been an inherent scepticism of technology, the convenience and universality of computers, smart phones, and other gadgets offsets this. The reliance of individuals on devices that operate in a paradigm of logical and mathematic programming is pervasive. Even if the common individual does not think about the epistemological methods of data processing being used in their gadgets, the results of technology and its influence on society is great. This has led to a society where high value, and a fundamental reliance, is now placed on the objective evaluation of information.

2.4.7. Contemporary Rationalism in Architecture

For designers and architects, this societal shift towards rationalism, and the development of rational and objective tool-sets have instituted new tasks within the practice of design.

The *scientific method* requires transparency, inscrutability, and repeatability; without these investigators risk epistemic divergence. Complexity, instability, and uncertainty are not removed or resolved by applying specialized empirical knowledge to *ill-defined* tasks. To deal with complex and *ill-defined* problems, professionals must be able to better define the problem, and then develop or determine appropriate solution methods.

Design however is *divergent* by definition. All design problems are by nature subjective, and by definition this makes them *ill-formed problems*. This fact creates allowance for different solutions to a single design problems, it is within this divergence that artistry and radical innovation find their existence. Design problems lack a clearly defined *start state, method,* and *goal state*. Each problem is a subjective interpretation, and the concept of the designer determines a unique goal state. As such, successful design is not only about problem solving, but is equally concerned with creative and appropriate "*problem setting*".

Rational methods of problem solving require *well-formed* problems, with a clear starting state, method, and goal state. This requirement for "proof" and "correctness" in rationalist methods is the fundamental problem when attempting to imply empirical processes onto design. The rationalist criteria of transparency, inscrutability, and repeatability are counterproductive on multiple levels to the justifiably subjective practice of design.

The availability of digital tools and programs for objective performance calculations, simulations, and even photorealistic rendering of design, still only "assist" in the development of a project. As requirements for performance, economics, and environmental accountability increase, design is increasingly being validated based on empirical, but unemotional values. Although perceived as "justification" by clients and specialists alike, a wide range of computation results do not necessarily synthesize into quality of space and excellence of architecture. The subjective, empathic, and emotional characteristics of design may prove too complex for computation, but they are still required.

---

[47] Paraphrased from: Chimero, F. (2010)

[48] Carr, N. (2010):172

2.5. Rhetoric and truth

Rationalism was presented in the previous section as the fundamental platform of logic and empirical reasoning. The primary advantage of the objective method is the ability to predict results for known systems, but this advantage is not applicable in design. If creativity was methodologically consistent, it could be taught – but it is not constant.[49] Predictability is moot in design due to the subjective nature of individual interpretation, experience, and skill.

Although not formally declared in design practice, alternative formal systems of thought that foster and integrate different types of knowledge (including knowledge from architecture and design) do exist, and have been developed in parallel with logic in the antiquity.

2.5.1. Confrontation of chaos

The search for "truth" as information, as knowledge, or as understanding, is the basis for all epistemological advancement, and the primary intellectual obstacle to this pursuit is complexity. As such, different methodologies, strategies and doctrines have been developed as tools to allow for the interpretation, development, and organization of thought such that truth can be derived or extracted from complexity. These methods, first developed in the antiquity, are entrenched in modern academia and guide and validate pursuits in the disciplines of the sciences, the arts, and philosophy.

Deleuze and Guattari delineate the three main forms of thought as philosophy, science and art, but show that what they all have in common is their use in the confrontation of chaos. The most important difference between science and philosophy however, is their different attitudes to chaos. Chaos represents unpredictable change and frequency, but not just disorder. "Chaos is an infinite speed of birth and disappearance." Science approaches chaos by trying to slow down and control the situation in order to understand and produce a generally valid, static knowledge. Philosophy by contrast, retains the motility, creating a situation of free, exploring thought.[50]

As human beings, we are always constructing our tools, models, metaphors, images and notions to help us handle, predict, and manipulate our changing context. Exclusive concentration on methods of analysis, deduction and proof, detract from the development of conceptual modes of thinking and creative development. If we accept that design fits into this context between doctrines of objectivity and subjectivity, then this raises the question of how to find the appropriate in-between point for any given design: Where is the balance of truth?

2.5.2. Variable truth

Socrates[viii] favoured *truth* above all other values, proposing that it could be discovered through reason and logic in *dialectic*. This stance recognizes that true reasoning and debate required the use of *logos*, (logic and reasoned discourse), but also *pathos* (an appeal to the audience's emotions), and *ethos* (credibility of the speaker). The resulting persuasion of truth came not only from the content of the message, but also from the rationality of both the speaker, and the inherent investment of belief made by the audience.

Given that design and architecture are polysemic in nature, does there exists an alternative strategy of thought which integrates both objective and subjective principles; one which can formalize the development of empirical truths, or *episteme*, within in the polysemic variability of design?

> *"I would define the episteme retrospectively as the strategic apparatus which permits of separating out from among all the statements which are possible those that will be acceptable within, I won't say a scientific theory, but a field of scientificity, and which it is possible to say are true or false. The episteme is the 'apparatus' which makes possible the*

---

[49] Brooks, H. (1967): p.89-91

[50] Deleuze, G. & Guattari, F. (1994).

separation, not of the true from the false, but of what may be, from what may not be characterised as scientific."[51]

Foucault's use of *episteme* has an interesting parallel to Thomas Kuhn's notion of a *paradigm*. While Kuhn's paradigms are a conscious series doctrines made by scientists, Foucault's episteme is akin to an 'epistemological unconscious' of an era; the combined knowledge and fundamental assumptions that are so basic that they are invisible to their constituents.

2.5.3. Analysis and synthesis

According to Professor Erik Stolterman[ix], two complimentary strategies of processing information coexist: The first is that of *analysis*, which applies the concept of dismantling complex phenomena to learn how they function. The second strategy is the process of synthesis, where assembling information related to phenomena creates a changed reality that, through authorship, is inherently understood.[52] Science uses analytical processes to make objective *predictions*, whereas design uses synthesis to make subjective *propositions*.

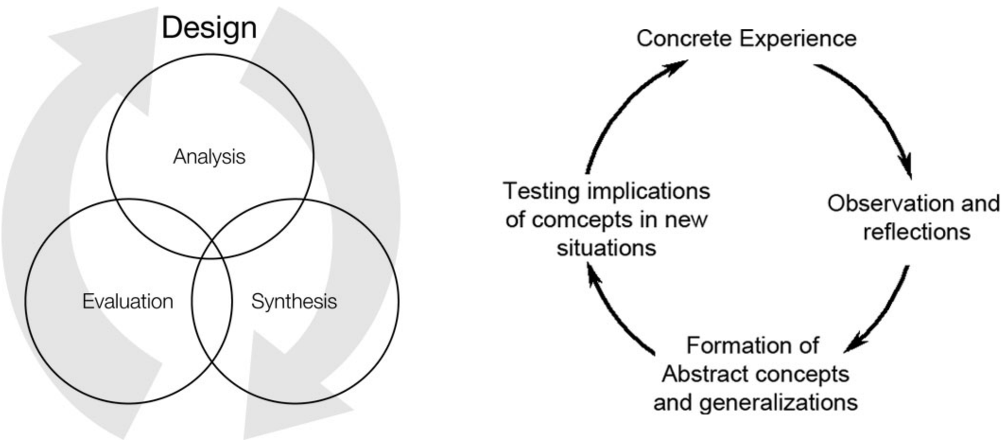


Fig. 2.5.3. Cyclical processes of design development: a.) Dilworth design development Venn diagram. b.) Kolb reflective model.

These processes do not give the same "truth", however they both produce information that can be used in strategies with different purposes. *Analysis* is undertaken when one needs to know how thing function. Synthesis is done to create something that does not yet exists, and in doing so it reveals both the role of the existing, and the potential for the future.

Although these processes can be seen as working in opposing ways, the results are not opposites. Against the backdrop of creative development, it becomes clear how *analysis* and *synthesis* can only be understood in connection with one another: Designers analyse existing design products in order to become better designers, and then produce design objects to extend their understanding of design. Through repetition this process of imitation and practice reinforces design learning and experimentation; successful rules become apparent, are understood, and accepted, whereas unsuccessful ideas recede. Through repetition experience is developed, and from this experience credibility and skilful prediction become possible. For this reason design is typically understood as an iterative process of analysis, synthesis, and evaluation.

Several models for design development have been proposed[53], and most follow the 3-phase cycle. Prof David Kolb developed this model further into a reflective model that identifies and highlights transformation of information into knowledge, the basis required for professional application. Kolb proposes that the knowledge gained from any situation is continuously

---

[51] Foucault, M. (1980): p.197

[52] Stolterman, E. et al. (2007)

[53] See section: 4.4. Design Theory

applied and reapplied, building both a design, but also practitioner's experiences and knowledge to be applied to subsequent work.

2.5.4. Logic and the domain of truth

In antique philosophy, Aristotle's "Analytics" is the preeminent doctrine of thought defining logic as the objective method to find truth. The main conflict between objectivity and subjectivity resides in the incompatibility of their versions of the "truth". It is possible to evaluate all of the objectively quantifiable components of a design, it is also possible to make a qualitative assessment of the subjective worth of the design, but there is no clear empirical way to reconcile the two. The recombination of the two sides is inevitably open for interpretation. To reconcile this issue, within the scope of this thesis, it is important to review the main issues of logic, and their use in the development of knowledge.

Aristotle is credited with the development of "Analytics", and specifically the development of the "logic machine".

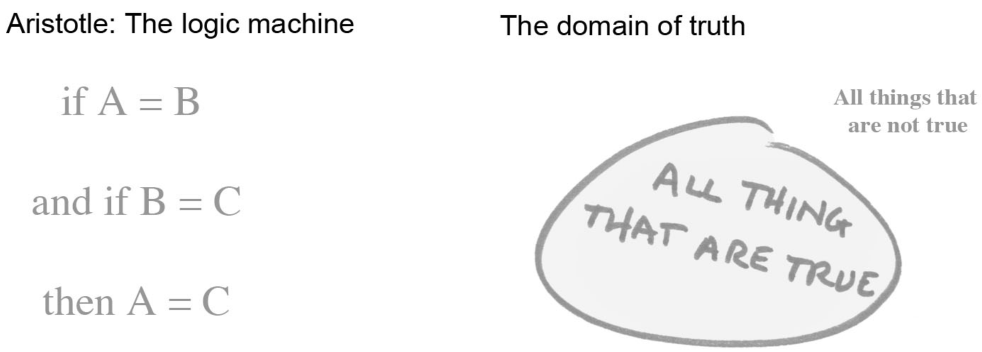


Fig.2.5.4. Logic: a.) Aristotle's "The Logic Machine" from The Analytics; the basis of modern deduction. b.) The domain of truth, and the resultant of 'not true': "where things can be other than what they are"

This correlation is the basis of inferential and deductive reasoning, the foundation for linear analysis, and tools of thought used to determine *episteme*. The equation as stated algebraically is straightforward, but outside of the realm of pure mathematics any critical observer will immediately question the equality by asking what the qualifiers are: What is being measured? What is the basis of equality? What contextual issues need to stated and be understood? Very quickly it can become apparent that this version of logic - when placed in the context of the complex and real world has limitations.

Aristotle qualified this theorem, by stating that the logic machine only works within the *domain of truth*: "*the domain of truth is where things cannot be other than what they are*". In this statement Aristotle developed two interesting concepts:

The first concept is that of qualifiers, statements taken to be true, which ensure that the interpretation of the logical statement is consistent across all viewers. These are the constraints, assumptions, and the medium in which the specific case of logic holds true.

The second concept states that there exists the possibility of a domain where "truth" is not the immediate goal, and in accepting, this the investigator must thereby also acknowledged that in creating a domain of truth, a reciprocal is also created such that if a phenomena is not part of A then by default it must be part of a realm defined as everything that is NOT A.

Pure logic uses these abstract tools of constraints and relations to limit and define the "domain" of a problem space; this defining of a domain is a philosophical method, and is already known to us as the defining of a "paradigm". As a paradigm is created, it defines all of the rules, constraints and phenomena of a given context; this is one of the fundamental rules of modern science and logic.

2.5.5. Illogical Design

Design, however, is not inherently logical. Design is based on individual interpretation, and it is a subjective product of opinion, instinct and the skills of the designer. Design is a craft of supposition "where things can be other than what they are", and when this possibility is invoked in logical processes the investigator is faced with the potential of the *paradox*; where two pieces of conflicting information exist, yet both can be "true".

This is the *designer's way of seeing*, he has the ability to see the real world, however he also has the ability to see a world where anything is changeable, adaptable and impermanent. Philosopher Vilém Flusser entitles this second reality "*the soul's second eye*".[54]

This notion of the paradox is the nature of a design proposal. By accepting that two fundamental ideas or outcomes can exist in the same "design space"[x], and that are both equally valid and yet are not the same (or even conflicting) the fundamental nature of design thinking is revealed. Even though this equality is empirically irrational, it is a demonstration of the domain "where things can be other than what they are". This paradox enables profound and creative thought by invoking "*the suspension of disbelief*".[xi] The reason that paradox, and the ability to temporarily suspend the need for rationality and logic is important is that like designers, and individual perception; people are also naturally paradoxical.

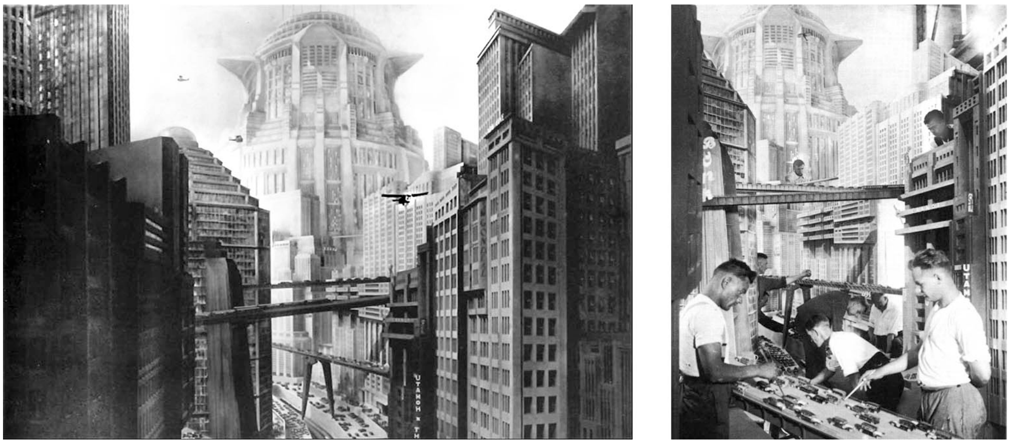


Fig. 2.5.5. Architectural suspension of disbelief: From the movie "Metropolis" (1927), Fritz Lang. The movie was set in a futuristic urban dystopia, and pioneered the use of technological special effects.

The main issue in exploring this paradox is that there is a need for the investigator (in our case the designer) to balance the two sides of the equation between analysis of "what is", and the synthesis of "what could be". The benefits of creativity in this exploration must somehow equal the costs of imprecision: The justification for design decisions becomes a responsibility for the designer who must convince the audience to invest in the hypothetical nature of the design. This is done through the practice of "*Rhetoric*": the act of saying "*what if…*"

2.5.6. Composition of rhetoric

Rhetoric, the counterpoint to *Logic*, was also developed in the antiquity as an art of *discourse* and a reaction to the emerging political process of the day: Consensus. As democracy replaced dictatorship; debate and persuasion emerged as noble pursuits, and the sophists responded with codification of philosophy and the structuring of *rhetoric*.

In Aristotle's "*Ars Rhetorica", dialectic* reasoning is defined as the mechanism for discovering universal truths, whereas *rhetoric* is the process for clarifying and communicating these principles to others. Aristotle conceived of *rhetoric* as an entirely different set of criteria and

[54] Flusser, V. (1999):.42

rules for the developing of creative thought, but furthermore it is also the art and study of the use of language with persuasive effect.

In the empirical paradigm, language is descriptive; it is used to label things and to enable communication; mathematics, and the abstract symbols used in equations are tools used for proofs and the representation of logical processes.

In *rhetoric* language is a tool for negotiation; it views context as variable and undetermined, this creates opportunity for new possibilities. Design that begins with possibility creates proxies for alternative futures long before they exist in material form. Viewed as a tool for the discussion and development of possibility, language is the raw materials for design. *Rhetoric* builds arguments or designs from language.

Rhetoric, as a second method of *discourse* complimented logic, and uses logic in combination with invention, judgment and decision as tools in the social process of debate.

In systematizing *rhetoric*, Aristotle identified three tools of persuasive audience appeal:

- *Logos:* the argument based on reason,[xii]
- *Pathos.* the appeal to emotion and sentiment,
- *Ethos:* the moral competence, expertise and credibility, demonstrated by the orator.

For structure, Aristotle defines two essential parts of rhetorical discourse: the statement of the case and the proof of the case. Cicero and Quintilian later refined and augmented the organizational scheme with an eventual composition of six parts:

- *Exordium*: Introduction, from the Latin term meaning "to urge forward."
- *Narration*: statement of the case.
- *Divisio*: the outline of the major points in the argument
- *Confirmatio*: the proof of the case
- *Confutatio* the discussion and refutation of possible opposing arguments
- *Peroratio*: the conclusion, a summation, refutation of those who might oppose, and a final plea and call for sympathetic belief.

What should immediately be of note is that this process not only defines argumentation and *rhetoric*, but also depicts both the *scientific method*, and contemporary legal procedure.

While the content, structure, and style of oration were (and continue to be) important, it is clear that the delivery and the credibility of the presenter are equally important to the persuasive power of the argument. Against the paradox of design, the effectiveness of the argument is not wholly dependant on rational empirical facts, but also on the subjective qualities that engage the audience and their trust.

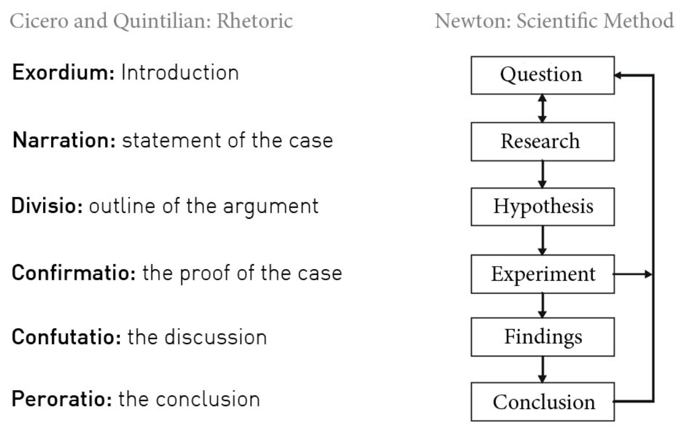


Fig.2.5.8: Comparison of Rhetoric from the antiquity to the contemporary Scientific Method

2.5.7. Opinion as doxa

The Swedish philosopher Mats Rosengren uses the term *doxa*: to define the amalgamation of convictions, traditions and models of thought that are held to be true within a specific society.[xiii] He argues that the incongruity between *episteme* and *doxa* is a misunderstanding of the roles and status of *opinion* in our production of knowledge. Rosengren further explains that science and philosophy have developed methods to separate the true from false, which is analogous to the separation of *episteme* (knowledge) from *doxa (*opinion*)*.[55]

Rhetoric by contrast does not discover episteme; it *creates* the "truths" (as *doxa*) that are needed for that specific moment. As such a rhetorical theory of knowledge sees all knowledge, all facts, values and *episteme* as contained within a *doxa*. *Rhetoric* infers that all presented issues can be considered a point of departure for argumentation.

If we accept that the common truth (*doxa*) is based not on empirical "proof" but rather, on good argument, belief and consensus, then the rhetorical approach emphasises the social reality, that all knowledge is a product of human understanding.

2.5.8. Rhetoric as design

The process of *rhetoric* involves making an inventory of the topic and the associated parameters that describe and affect it. The orator must then arrange and deliver arguments based on emotions, reason, and confidence, so as to engage the emotions, trust and belief of an audience. This process and the forethought, strategy, and planning required shows a clear analogy to the other traditional activities of design: argument is a well-designed *dialectic*.

Forethought is an architectonic process, concerned with discovery, invention, planning and argument of a point of view or design. It is the mastered task of making a design, but it is also the process used to prepare for argument within *rhetoric*. Already in ancient *dialectic,* systematic forethought was developed in the preparing of words, organization of thought in narrative, and the development of credible logic that would enhance the argument such that it would be accepted.

> *"Design is the art of shaping arguments about the artificial or human-made world, arguments which may be carried forward in the concrete activities of production in each of theses areas, with objective results ultimately judged by individuals, groups, and society."* [56]

In the approach to a design problem, context is analysed and a determination is made as to what is missing, incompatible, but also what is beneficial. This is the basis upon which an argument is formulated: *"Given this assumption, then what if this – were to occur"*. Architectural proposals are therefore a rhetorical exercise of the designers with themselves, and also (later) of the design team to the external players of juries, clients, critics, and users.

The connection between a designer, the intended user, and the goal of design investigation is based in *empathy.* A *designer* is not trying to test a theory or validate research, that is a work of empirical assessment. The designer has two interrelated tasks: First is to understand the problem and needs of a design situation such that this allows for development of a solution; Second is to synthesize a solution that addresses the *real* issues, not just the *perceived* issues and doing so in a way that results in an empathic design for the intended user.

Just as Rosengren states that *rhetoric* is a producer of *doxa* and knowledge, the architectural project or design proposal is a catalyst for a specific future potential; to show what is possible and the values it would entail. The presentation and defence of a design includes argument that it is reasonable, emotional (beautiful, engaging, and desirable), and fitting (ethical and proper), but the design is qualified and evaluated through a "filter" of outward credibility and empathic conviction of the orator.

---

[55] Rosengren, M. (2008):51

[56] Buchanan.R (1995) :46

"Rhetoric is of great importance within all architectural practice, you have to present good arguments for your proposal, and be able to communicate it with a broad audience. Within architectural competitions the importance of rhetoric is especially obvious. Elisabeth Tostrup has studied this specific field of design practice. (Tostrup 1999) The winner of an architectural competition is not the most objective presentation, but the designer who is able to create a proposal based on the best arguments. Tostrup states that the material of the competition expresses the hegemonic architecture of its time – the network of political, economic and social relations where some actors have a dominating position – and the proposals are trying to communicate its arguments within the field of prevailing values, thoughts and ideas."[57]

For designers, the language used to argue a design is different from that used to explain decisions. On one side there is an implicit engagement of the sympathy of the audience, and on the other there is an explicit need for objective justification. In *rhetoric*, design is not a single language, but rather it has dialects for different purposes, and effective and convincing communications are an equal part of design process.

2.5.9. Future rhetoric

"Architecture is differentiated from building in that it is deemed to induce sensations of delight and wonder in its observers."[58]

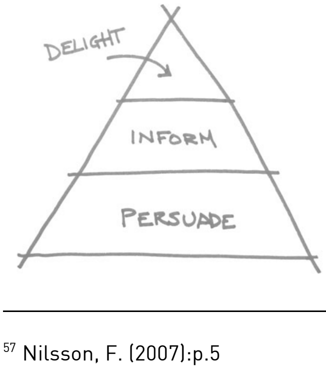
The risk of neglecting *rhetoric*, persuasion, and empathy in favour of rationalism, is that in the effort to optimize and create efficiency and performance, the design becomes less engaging, less emotional and less delightful.

In discussing architecture and delight, philosopher Alain deBotton, states: "*…of course the real function of a building encompasses both sheltering and what Ruskin calls "speaking". There is a lovely quote from Ruskin who says that buildings shouldn't just shelter us but should also speak to us. They should speak to us about all the things we think are most important, things that we need to be reminded of on a daily basis. The idea is that buildings can be the repository of certain values and ideas and that they should reflect these back to us to inspire us…*"[xiv]

The designer and writer Frank Chimero formalizes this importance of emotional connection to architecture by stating that the goal for successful and creative design is to invoke three progressive reactions in its audience.

Through the successful use of rhetorical persuasion design can: first, *Persuade* the viewer of its merits and value. Second, and only once it has convinced them to pay attention, design can *Inform* them about the influences, context, and other intentions that led to the design. Finally, and only if it has been successful with the previous tasks, a design can engage the interest and emotions of the viewer, with *Delight*.

The willingness of the viewer to contemplate information creates a context and understanding of factual and emotional content of a design, however it is only upon making this commitment that *delight* can occur.



"Delight comes at the point where clarity and surprise convene. Delight is the tip of the Design Nobility Pyramid, and it represents the highest form of success. Delight is a designer's 'super power' in that it has the ability to engage emotion: we can make someone 'feel'. This is a reaction that is most often associated with the domain of art. When understood in this way the mind-set of the designer changes, from thinking of design practitioners as communicators to believing that we are humble gift-givers."[59]

---

[57] Nilsson, F. (2007):p.5

[58] Gage, S.A. (2006):p.777

[59] Paraphrased from: Chimero, F. (2010)

2.6. Technological adoption

"When you wish to achieve results that have not been achieved before, it is an unwise fancy to think that they can be achieved by using methods that have been used before"[xv]

- Sir Francis Bacon

Historically, until the time of the Enlightenment and into the beginning of the industrial revolution, architecture (entitled at that time "building") was one of the leading disciplines for innovation and the development of scientific knowledge. The Architect, originally called " the master builder" was both a skilled craftsman, with knowledge of all trades needed for the design and construction of a building. But the historic role of *master builder* extended beyond the practical application of their skills and knowledge, to include research, development of knowledge, and invention.

The progressive shift in systems of thought instigated in the Enlightenment slowly shifted the importance and responsibility of invention away from the architect. With the evolution of the engineer, the scientist, and other specialists, architects have become associated with design and its incorporation of objective principles and innovation that have been perfected in other disciplines.

Fig. 2.6. Drawing of Hugh Libergier, Master Builder for the Reims Cathedral (1263); note the model held in his hands. Tombstone of the Master Builder. (source: Roth, M. (1993): Sketch by J.B.A. Lassus)

2.6.1. Adoption and adaptation

"The effects of technology do not occur at the level of opinions or concepts, but alter sense ratios or patterns of perception steadily and without resistance."[60]

- Marshall McLuhan

Architecture has become a field where the implementation of technical innovation is a product of collaboration, adoption and adaptation. Given the emphasis placed on rational valuation and justification, the role of the architect risks being further shifted from substantial management, to stylistic design and layout.

Currently, the conventional method of advancement in architecture is incremental innovation. Due to the traditionally cautious nature of the industry (and the associated issues of liability and economics), radical innovations in the profession typically come from outside of the field of architecture.[61]

Architecture is somewhat unique in the design-production industries in that each project is (typically) a unique "one-off" project. Because of client demand for uniqueness, bespoke response to context, and the specifics of function and client requests; each architectural project comprises design research and development, and can be considered a distinct prototype, but an archetype that should achieve the quality of a finished project.

The high investment costs associated with innovation, combined with the lack of opportunity for repetitive standardization or optimization methods (uniqueness = no mass production) means that architectural practitioners generally look for economical and practical means of

[60] McLuhan, M. (1994, reissue): p.31

[61] Kolarevic, B. (2003): p.10

innovation that satisfy professional and client needs. In the recent past the main method of process development has been to adopt and adapt innovations from other disciplines.[62]

The automobile, aerospace, and shipbuilding industries are all design and engineering industries with similar production factors and a product scale similar to architecture. As each of these industries has high potential for economic capitalization of innovation (mass production or high returns), there is significant investment in design and production technology and optimization. Automotive design and engineering is capitalized based on the issues of mass production and optimization; aerospace on the economics of performance, safety, and competition of technology; while shipbuilding is capitalized on performance, operations, and construction efficiencies.

> *"To be innovative, architects must become more responsive to their users and environments. In other words, they must incorporate feedback from their physical and cultural contexts rather than relying solely on conventional analytical or internal processes of development, from design to construction."*[63]

With new and greater focus on digital processes, optimization, and environmental performance, designers and architects have now shifted their focus beyond the production industries, to now include advanced scientific and digital research as muse for design. Technocratic architects are adopting algorithms and methods taken from advanced computer science programming, they are adopting concepts from current biology and environmental research, and have already implemented new programming methodologies based on abstraction graphing taken from electronic engineering.

Architecture as an industry does not have the same funding and opportunity for advanced developments of tools or iterative optimization. As each architectural project is (typically) intended as a unique design, with specific customization and relation to its context, function, budget, and inhabitants the emphasis of the profession is on product rather than developing tools and process. Yet, each project must still also respond to the commercial and societal expectations of their clients and must respond to evolving regulation and contextual factors. As such, avant-garde architectural concepts are increasingly being learned from the advancement of sciences and the commercial industries, and as technology becomes available the profession adopts, adapts, and implements innovation.

2.6.2. The "trickle-down" effect

The "trickle-down theory", was developed in the field of economics as "trickle down economics" and was popularized in the Reagan-era 1980's America. The theory (paraphrased) states; *as the rich become richer they will invest more capital in larger infrastructure, and this in turn will create opportunity downstream for the more needy.*[xvi]

Technological development in industry, and technological adoption within architecture has a strong affiliation to this theory. Architecture has become a "needy" adopter of technology that is invented, perfected, and popularized by the better-capitalized industries. New technologies are developed, perfected, implemented and eventually become entrenched in the advanced industries industrial process. As the equipment, process knowledge, and experience all become increasingly pervasive, their overall exclusivity and value diminishes. As newer innovations (be they iterative or radical) are introduced to industry the existing technologies and their knowledge becomes less valued, and therefore more readily available *downstream*.

As new innovations take place in the aerospace, automotive, shipbuilding, and industrial design fields; their existing technology becomes less costly to use, and are adopted by lower capitalized professions (such as architecture and construction manufacturing). Computer numerically controlled production machines were first invented in the 1960's; the current wide-scale adoption of these machines in (1st world) construction manufacturing is not an issue of invention, but rather it is an issue of availability, cost and availability of experienced

---

[62] From: Kolarevic, B. (2001):p.10

[63] Rahim, A, (2003):p.3

users. The cost of implementing a technology in any industry is a direct cost/productivity calculation. When the balance point has been achieved a “new” industry will find value in using the technology. This is the trickle down effect of technology.

As the computer has become increasingly ubiquitous in contemporary society, the cost of computer hardware has decreased and the power of computation has reciprocally increased.[xvii] Access to increasingly powerful computing machines has made possible the adoption and adaption of advanced scientific process into design.

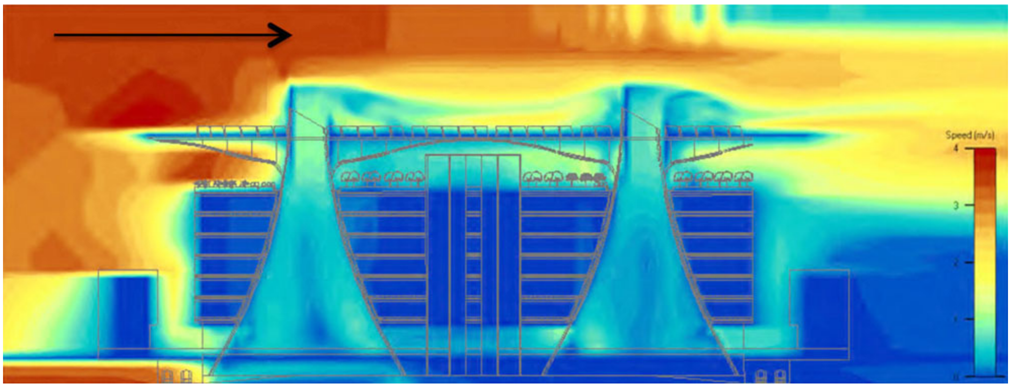


Figure 2.6.2. Computational Fluid Dynamics simulation of “Masdar Headquarters”, UAE; Smith+Gill Architects. CFD software was originally developed for the aerospace and auto racing industries but has now been extensively adopted and adapted for architectural usage.

Architecture is, by nature, a field where analogies and abstractions are used as conceptual devices to position and develop subjective design. By simply increasing awareness of new and emerging research, designers are able to adopt and re-purpose it for creative use in justifying, expressing, and improving design.

2.6.3. Irony of youth

As Max Planck reminded us previously[64], acceptance of a new paradigm is clearly favoured by *“a new generation who grows up and is familiar with it.”* Within architectural practice, and its tradition of being a master-student profession, this creates an irony that those architects with experience in cutting-edge of technology also typically lack significant experience in practice.

> *“Small to medium sized studios – especially those set up by graduates with experience in computing – have to participate in most stages of the design workflow and thus are able to integrate computing better early into the briefing and design concept stages. However, their very size or experience doesn’t allow them to build complex buildings or masterplans where computing is more appropriate. Thus, they usually apply computing to sculptural aspects and installations. The other domain for young studios is to consult medium to large offices on specialist aspects, such as cladding packages or structural and construction solutions.”*[65]

The tools at the command of these emerging “digitally empowered” architects can handle complexity at an unprecedented level, and yet the incongruity of their experience doesn’t grant them access to such scale of projects. The result of this is that computation currently resides in a realm in-between practice and theory, and it is brought in to either area as needs (of either the established practice or the aggressive upstarts) dictate.

2.6.4. Technology adoption into practice

All large architecture practices now employ advanced digital computation tools (in some capacity) within their architectural development work. While the application of computer-aided design is mostly used to digitize and enhance established workflows, new applications

[64] See: “2.1.2.1. Paradigm-shift”

[65] Derix, C. (2004):p.567

and concepts are emerging that challenge this status quo. Decisions concerning the adoption of technology, however, are not solely concerned with creativity and productivity.

The act of changing existing workflows through the implementation of new technologies carries risks, and within a service profession (and one with weak margins such as architecture) risk is to be avoided. As such different practise have adopted different strategies to the adoption and implementation of technology in their working methodology.[66]

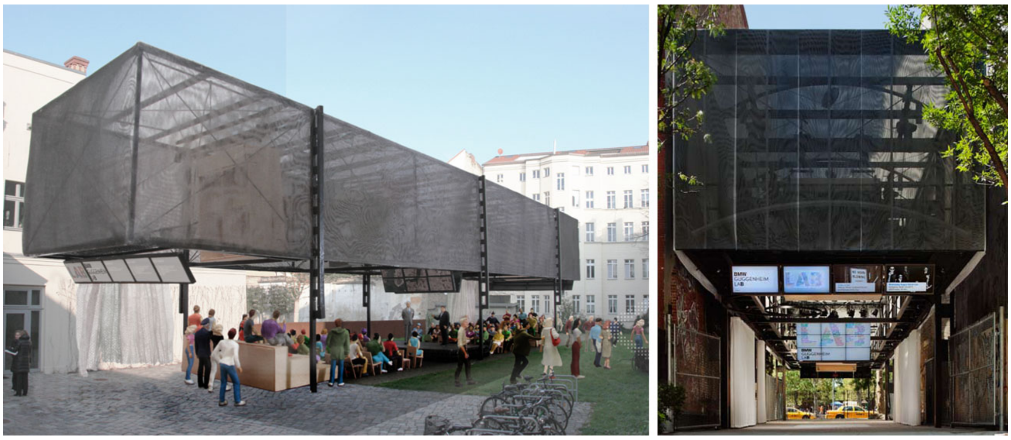


Fig. 2.6.4. BMW-Guggenheim Lab. (2011), Atelier BowWow. Travelling lab and showcase for BMW and the Guggenheim foundation. Adopting technology from the auto sector, the structure is built in Carbon Fibre for lightness stiffness, and ease of assembly. The lab has been installed in New York and Berlin.

Understanding both the implications and the “possibilities“ that technologies bring to a practice is key to the successful implementation technology in design. As technology develops, it (metaphorically) pulls and pushes the profession with it. High level, advanced The technologies, currently being investigated in academic realms of science and engineering (and to a lesser extent in architecture)academia are still trickling down to practice, but large scale and adoption is still scant. The Does this delay in the adoption and adaption of technology typically ensures that if a paradigm is changing, then the profession has a clear warning, and is able to mediate risks accordingly. But as well as a clear opportunity for early adopters there are clear, but risky opportunities for novelty and advancement.

2.6.5. Future adoption

Understanding the *trickle-down effect,* and the *adoption and adaption* of external innovation in architecture are important in that when combined, they aid in making future influences and processes of technological advancement in architecture predictable.

In the context of this thesis, there is significant value in prediction, for two reasons: First, It introduces and legitimizes the knowledge that architecture does not practice at the leading edge of technological, industrial, or scientific innovation. Secondly, it shows that a practical method of predicting “near future” innovations, specifically in design and production technology, is to look at the current technology being implemented in other “cutting edge” industries and fields of research.

These two revelations will allow for further investigative research into emerging design and production technologies: Additionally this understanding will inform the thesis conclusions, when looking at emerging technologies and evaluating what effect they will have on the future development of the architectural-technology paradigm.

[66] See: “3.3.2. Technology in Practice”

2.7. Design in the age of rational tools

> *"Design is the art of deceiving nature with technology, to surpass nature with the artistic, to construct machines that in an artful way make us free artists."*[67]

A designer working a problem is continuously engaging with, reflecting on, learning from and reformulating the problem at hand. The application of strict rules is the opposite of design, while if there is no flexibility of process, then *creativity* and the design will not have an ability to respond to knowledge or emerging conditions as they arise.

The use of tools, and specifically the digital programs, often force a rationalist doctrine onto the working method of their user. When a designer chooses a specific tool, he chooses to conform his working method to take advantage of the tool's inherent potentials; but the opposite of this is also true. By choosing a specific tool, the inherent capabilities of the tool can inform the intellectual approach to a specific problem, and this can give the design new conceptual insight into an innovative design solution. Any tool can be chosen to promote efficiency, but understanding that the choice of a tool, be it a physical tool or a conceptual one, will bring new possibilities, insight and potentials all while also implying constraints onto the user. As with the objective and subjective nature of design, it is up to the designer to find the appropriate balance.

The primary motivation for the thesis is to support and investigate the idea that artistry, creativity, and innovation in design can coexists, and even thrive with the use of objective and technologically derived processes and tools.

Examining how architecture and design have evolved implies understanding the inherent philosophies and methods of *rationalism* and *rhetoric*. To investigate this topic, the thesis will apply both epistemological methods to design and technology in a comprehensive but complimentary manner.

Knowing now that architecture is typically a late adopter of technology from parallel disciplines and having a sense for what scientific research will have potential to change architecture (even at an abstract level) enhances the investigators powers of prediction with respect to technology.

The thesis is in its own way a design. Like any project it has begun with an ill-formed problem composed of episteme, doxa, components, and relationships; and the thesis seeks to synthesize a result that will engage the reader. The thesis argumentation needs to present rational and *logical* development of research, engaging and novel *insight*, the *credibility* of chosen methods, and an ability to communicate the resulting knowledge succinctly to the audience. Just as *dialectic* can be identified with the processes of design presentations, so too can *rhetoric* be associated with structuring research.

[67] Flusser, V. (1999):p.40

Endnotes:

---

[i] For a greater analysis and interpretation of this see "*Appendix 01: Industrial ages*"

[ii] Definition: Having multiple meanings which are simultaneously true

[iii] from: *Weltanschauung*: a parallel but more comprehensive concept: the framework of ideas and beliefs through which an individual, group or culture interprets the world and interacts with it.

[iv] In this thesis I will differentiate the technological definition of (systems) *architecture* from the profession of designing and constructing buildings, by italicising the word.

[v] Extracted from: www.gilbrethnetwork.tripod.com (accessed:06.04.2011)

[vi] For a critical history of technology adoption by contemporary society see: Postman, N. (1993) "Technopoly: The surrender of Culture to Technology".

[vii] For a critical historical review of architectural progress from the 1960's-90's, see: Ghirardo, D. (1996) "Architecture After Modernism."

[viii] Socrates was the teacher of Plato, who in turn had Aristotle as his apprentice.

[ix] Professor of Informatics and Design; Director of the Human Computer Interaction Program, at the School of Informatics and Computing, Indiana University.

[x] "Design space" of a problem is a concept used to denote all of the requirements, constraints, influencing parameters and other context of a specific design problem. Each of these influences are themselves variable, and it is this within the variability of parametric factors that we define the "design space" of an architectural problem. See: Loveridge, R. (2011) *"The Digital Design Paradox"*

[xi] The "suspension of disbelief as a concept is a *quid pro quo*: the audience tacitly agrees to temporarily suspend their judgment in exchange for the promise of other value. This concept is originally extracted from: Todorov, T. (1975). "*The Fantastic".* Cornell University Press.

[xii] Carl Jung, contrasted the rational and decisive logos with the emotional and mythical elements of mythos. This contrast was seen to represent science vs. mysticism, reason vs. imagination, or even masculine vs. feminine.

[xiii] From the ancient contrast between *episteme* (knowledge), and *doxa*,(what is believed to be true): Rosengren, M. (2008) "The Cave of Doxa": p.51

[xiv] Transcribed from audio podcast: deBotton, A. (2007) *"On The Aesthetics of Architecture"*

[xv] Attributed to: Sir Francis Bacon. by: R.A. Mashelkar, in TED talk: "*Breakthrough designs for ultra low-cost products.*"

[xvi] See: http://en.wikipedia.org/wiki/Trickle-down_economics

[xvii] This is formalized in Moore's Law. See: wikipedia.org/wiki/Moore's_law

3. Technology

"For centuries historians and theorists have traced and debated technologies role in shaping civilization. Some have made the case for "technological determinism" where technology progresses as a force outside of man's control. On the other side of the argument we have instrumentalists, who argue that technology are neutral tools, entirely subservient to their users. This is the more commonly held view, perhaps partly as people do not like to consider their free-will is lessened by technology."[1]

- Neil Carr

Architectural theory and practice are both heavily influenced by outside inspiration. Technology has been a prime motivator in architecture since its inception. The strength of this connection to design and other disciplines occurs in two forms: either directly as design mediating tools, or indirectly as the basis for information translation and dissemination. This duality of technology demonstrates the magnitude of its potential and impact.

This chapter is divided into two main parts:

The first part focuses on technology itself, providing definitions and brief overviews of how each "tool" fits into the digital chain, with insight into how techniques and concepts have been explored in this research. The section concludes with a brief overview of technologies and projects that exist in industry or research that represent the state of the art of this field.

The second part of the chapter focuses on the influence of technologies on architectural process and specifically on the concept of the digital chain. The focus remains on clarifying the role of technology, with insight into its affect on theory and practice.

These sections are intended to lay a foundation of technical knowledge for the rest of the thesis. In presenting this information as a complex interlacing of issues (rather than the typical academic analytical listing of points) the intention is to show that these issues are all interconnected. This issue of interrelatedness is what gives the topic its importance, and shows that the networks of knowledge are just as complex as the technologies being investigated.

3.1. Digital Technology

"The computer is more than a simple tool. It is a machine that is imbued with (preprogramed) responses to specific inputs, but it is also a medium that exerts an influence over its user. Because of the very specific syntax and operational requirements the use of a computer requires adjustment in working methodology from its operator. This adjustment, of method, of organization of data, of workflow is the payoff for the promise of improving working potential and the ability to manipulate work in ways not possible outside the computer."[2]

– Neil Carr

3.1.1. The computer

Man develops tools to augment their abilities; the development and evolution of the computer has permitted both the creation and handling of vastly increased amounts of information. The result of this has been the reciprocal effect of an exponential increase in access to knowledge, and a resulting need for more information processing capability.

[1] Carr, N. (2010): p.46
[2] Carr, N. (2010):p.75

The modern "computer" was conceived as a general-purpose computation machine, whose fundamental characteristics are that it is a programmable and can automatically carry out sequences of arithmetic or logical operations. The nature of its programmability means that it can solve any kind of problem that can be logically encoded. Numbers are a tool used to count, but they are also abstract symbols used in mathematics (which itself is a conceptual tool), which provides a logical and analytical basis to model analytical situations, and the ability to "calculate" these models then becomes the potential to predict change in the models. Calculation is the basis of prediction, and therefore simulation.[i]

3.1.2. The information machine

The capability to innovate is directly related to the understanding of a problem, applying experience of similar conditions, and speculating about potential solutions. When undertaken by the human brain, problem solving in limited by the mental abilities of the person. When a problem is layered and intricate, the "scale" of information can easily exceed the ability of a person to calculate it; the problem, quickly becomes too complex. The computer is therefore a tool to augment mans ability to deal with complexity.[3]

Fig.3.1.2: "The Information Machine" (Charles and Ray Eames (1958)). Video for IBM Corporation to explain the concept of the "computer" to the general public: (still from video - ref: YouTube).

As societal understanding and expectations for control of context increases in resolution, computation is being increasingly used as a tool to manage these scales of information. Design professionals are progressively using computers to manage complexity, speculate about problems, and to develop new methods of design.

To begin at "first principles"; design computation (and logical processing) is useful in three elementary capacities.[4]

- it can be used as a *control* mechanism
- it can be used as a platform for simulation, and evaluation; a *speculation* mechanism
- it can be used as a logic *processing* mechanism

3.1.2.1. Control:

Digital programs are instructions sets to solve complex logical problems. Problems are encoded with mathematical representation, and software is used as a "translator" to contextualize input for the computer and output for the user. The most significant power of computation is that intermediate solutions are saved in memory until required, allowing for highly efficient and complex series of calculations to appear to the user as

[3] From: "*The Information Machine*" (IBM film 1958).
[4] From: "*The Information Machine*" (IBM film 1958).

single operations. The use and flow of information within the system is automated and software is encoded methodologically so that it is able to deliver appropriate information at the correct point in the process.

Computers can be programmed to respond to specific types of input, including data, clock time, and other "stimuli" from devices that may be incorporated into hardware system. The ability for a computer to be "aware"[ii] of contextual parameters, and to follow complex instruction sets, enables computers to be used as *control* devices. This is the basis for the field of digital *cybernetics*[5], and allows computers to be used as control devices.

The process of developing software is a strategy and a design unto itself. The code must precisely define the *start state* and *end state,* and also encode the explicit instructions that will give them the desired result in a specific and known case. Once the instructions have been encoded, the same process can be used with variable data, and the resulting output and patterns define the ability of the computer to process or solve problems; this is the digital analogue of the empirical *scientific method* of experimentation.

With adequate programming, computation can deliver complex numerical results that are "translated" to be comprehensible at the human "scale". The *control* of information is beneficially used to remove menial tasks from workflow such as repetitive tasks within statistics, accounting, inventory, and logistics.

In design, digital tools enable the abstraction, modelling, and imaging of geometrical information according to the mathematical rules of transformative and projective geometry. These functions and the ability to render visual "solutions" are at the root of all CAD and 3D modelling software.

In a more explicit definition of "control", the capability to calculate and follow complex instructions at a mechanistic degree of precision and timing, makes the computer an ideal tool to augment the ability "to control" machines. Digital control drives all common peripheral devices and has extended into physical production and modelling. Obvious examples of this range from display screens and printers, to computer numerically controlled manufacturing machines and robotics.

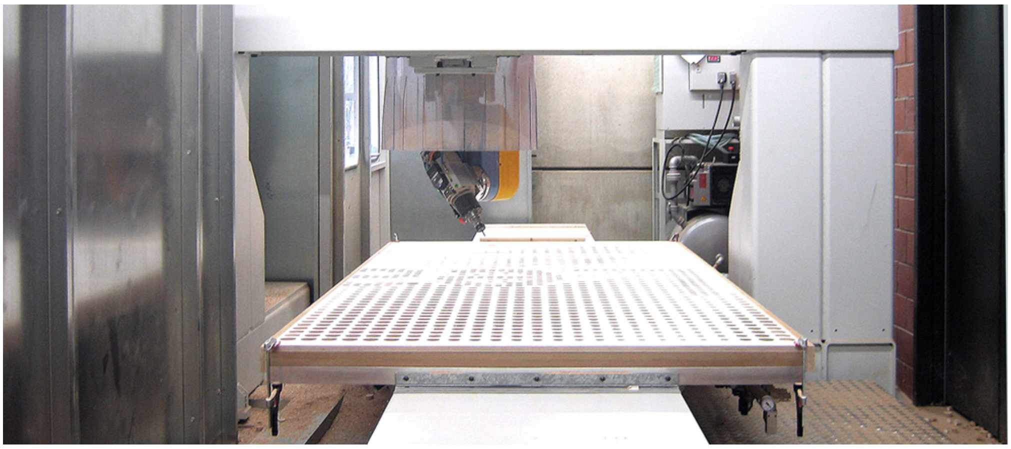


Fig.3.1.2.1: "Computer Numerically Controlled" (CNC) fabrication machine: MAKA MM7S – lapa lab.

3.1.2.2. Prediction:

Complex modelling can now be undertaken with commonly (and economically) available software and computers. The capability of the computer to simulate conditions and processes is an augmented variation on the ability to manage complex instructions.

---

[5] See: "4.1. Systems Theory"

If a complex system is modelled with enough *resolution* of components and interactions, then the model is reduced to a mathematical and logical problem of simulation and probability. By encoding a model with *parametric* variables, a systems model can be rationally adapted and used for prediction of differing variables, contexts, and conditions, and as such the process becomes a prediction tool.

Fig.3.1.2.2: Simulation: a.) Digital simulation rendering, b.) Photo. Rolex Learning Center, Saana.

Speculating is the ability to predict the effect of an action, before taking the action. This is the basis for much of the way that a computer is used in design; the computer provides a temporary medium for the creation of impermanent design. Visual simulation of geometry, materials, context and other visual and aesthetic parameters are calculated for digital rendering, animation, and visualizations, all being inherently changeable. Analytical modelling tools are used augment this prediction practice by providing capabilities of simulation, analysis, and evaluation. These processes are used in many design fields, and are slowly "trickling down" to the architecture and building professions.

Prediction is a fundamental process that provides the user with adequately informed speculative information such that it is possible to make educated decisions.

3.1.2.3. Processing:

The technical constraints to modelling and simulation are the processing power and availability of memory within a computer system. With current high-end computers[iii] and software, specific model definitions may represent entire processes, behaviours, contexts, constructions and conditions. The use of these simulation-models can be used (within a degree of abstraction) to predict performance potential and response over time.

The creation of predictive models is an elaborate process to implement due to the complexity of encoding physical and behavioural phenomena for the simulation. Demands placed on the user for precision of input data and precision of context modelling, combined with the requirements for processing power and memory, are such that the process has a very high front-end investment.

The combination of *parametric* modelling, computation and simulation, permits a complexity of problem solving that returns not one single solution, but a range of possible solutions. If this process is then combined with an evaluative assessment program, the model becomes a tool for determining (statistically calculated) performance targets.[iv] This process of not only predicting performance, but also determining which conditions produce ideal optima allows for highly informed decision-making, and by extension enhances design decision-making.

If the data from the evaluation is "fed-back" into the modelling phases of the design program an adaptive design "loop" is instituted, which has the autonomous ability to iteratively refine the design towards an explicitly stated goal[v]. This is the definition of a generative design, where a system of programming can generate a solution for an explicitly stated problem.

Programs can also be encoded to have complex programmed interactions at higher levels of workflow. By linking specialized software programs across the level of the computers operating system, computation becomes a method of modelling and processing entire workflow patterns.

Through the use of databases, feedback methods for input and output, and systems level programming, different software can work in concert to create complex autonomous digital workflows. This potential, if used creatively as a tool design can create results of exponential complexity.

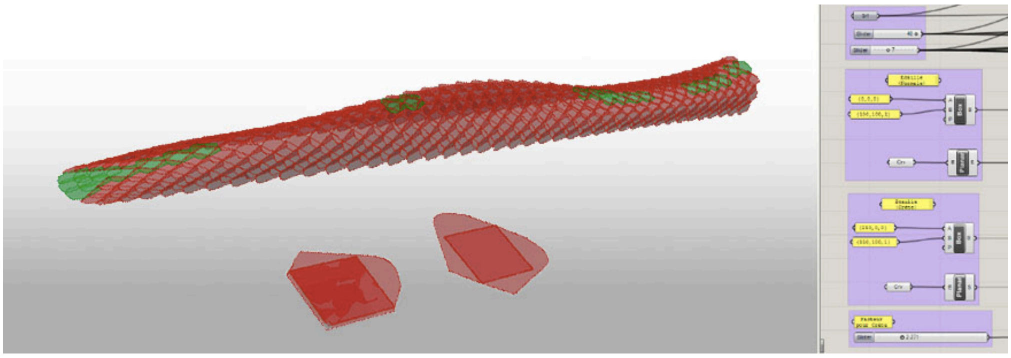


Fig.3.1.2.3: Digital processed design: Automated panel generation, using Grasshopper. DD+P11: authors: Davide Di capua + Jakob Lock.

Finally, processing can be taken to a higher *order* where solutions produced from processing of design problems can be used to refine and change their own programming: results from on iteration of a process can be used to alter the processes used to create, simulate, evaluate and refine the solution. This is called *second order cybernetics,*[6] and it infers a process where the evaluation of a design leads to an *automated* change to the overall design process itself – a rudimentary, directed and highly abstracted form of design *learning.*

These three functions provide a clear reference of the information manipulation currently possible with computers, however this reference is in a persistent state of evolution. In both scientific research and science fiction there is an eventual goal a form of Artificial Intelligence. Although significant progress has been made in this research field, computers currently are not, in any specific manner sentient or intelligent. Cognisant intelligence, freedom of thought, irrational association, and subjectivity are all still the epistemological realm of humans.

3.2. Design Technology: State of the art

This chapter will briefly introduce and define the main "cutting edge" concepts, technologies, and techniques investigated in the course of this thesis.

3.2.1. Digital design methods

With the advent of the modern electronic computer, digital drawing programs were invented and developed in the 1960's.[vi] With continual development, propagation, and the eventual integration into professional design methods, the computer is now the dominant media for development of architectural design.

3.2.1.1. Digital geometry

Digital geometric primitives traditionally consist of point, vector, curve, circle or ellipse, polygons, and plane. In 3D applications, geometric primitives will also include sphere, cube, cylinder, cone, pyramid, and torus[vii]. Common *non-uniform geometry* types that are supported by contemporary CAD software include NURBS, NURMS, Sub-division surfaces (T-spines), polygon meshes, and Bezier patches. Each of these geometry types is defined by how the geometry is encoded and the mathematics used to determine transformations. What makes these geometry systems attractive to designers is the ability to create complex geometries, which are still readily controllable within the software.

[6] See: "4.1. Systems Theory"

The wide use of descriptive geometry in architecture shows the importance of applied mathematics in the field of architectural design. CAD tools assist the designer in engaging these techniques and manipulating geometry, however they also isolate designers from basic geometric understanding. This is both problematic for the design, and also constraining to the designer and their ability to envision geometric opportunities. If a designer wishes to engage geometry in design at a more advanced, intensive, and intelligent level, they still need to have a sound comprehension of the fundamental mathematics behind form.

3.2.1.2. Digital drawing methods

The most common approach to digital design is to use the CAD software as the digital analogue of drawing, drafting and modelling. It allows the user to create, manipulate, transform, and make advanced transformations (such as Booleans) using the tools provided in the Graphical User Interface (GUI). As both the complexity of software and the requirements of users evolved, available tools have increased to include tools that are now specific to digital medium and have no "paper" analogue.[viii]

The use of tools to "draw" architecture is fundamentally reliant on a strongly developed skill and knowledge of the software, its capabilities, and its user interface. Before the designer can freely and intuitively express their design, their skill with the tools must first be developed to a level of high proficiency, this is the inherent limitation of this method.

CAD software allows for graphical interaction and manipulation of geometric representations of design. The fundamental issue though is that the geometry depicted on the screen is a graphical re-representation of logical and mathematical functions that have been calculated according to the rules of the software programming. The operating medium of the computer is computation and logic.

3.2.1.3. Formation methods

The mathematical and logical potential of the digital medium has transformed the concept of form into the concept of *formation*, (form + information = formation)[7]. Digital formation models are "*a radical and even antithetical departure from graphical manipulation of formal and syntactic representations.*"[8]

Programmed design uses text based "scripts" (programmed in the syntactical digital code), and submits them to the software as command instructions. *Scripts* are sets of explicit instructions, which may be a basic operation or a complex procedure using logical operands and variables to control processing. The use of scripting and the code editor bypasses the GUI in favour of the commands being processed directly by the software. Programming methods can be subdivided into a range of types, based on their level of complexity, syntax of language, and how they interact with the computer.

3.2.1.3.1. Macros

A software macro is a set of specific instructions codified as a single defined procedure. Used for making automated sequences of multiple computing instructions as a single "program", a macro may accept user input, so as to customize the result. Macros give users the ability to create multi-function tools based on existing tools. Macros are used extensively in graphics manipulation software such as Photoshop, but they also form the basis for many CAD programming languages such as AutoLISP[ix] and MEL.[x]

3.2.1.3.2. Scripting

Scripting is the process of encoding instructions that allow for complex control of tools or logical instructions within one or more software applications. Scripting languages are high-level programming languages using natural (English) language elements,

[7] Oxman, R. (2005)

[8] Oxman, R. (2005)

making them easy to read and understand. The encoding text is typically viewable within a "script editor" window in the program.

Common scripting languages[xi] used between applications permits for cross-platform interaction and automation, and can be used for control of software tools, data input/output, and connections to external databases and other software. Scripting languages can be also programmed to operate with data feedback, giving potential for higher *order* adaptive algorithms and models.

Scripting is becoming a popular tool in design[9] as it can automate complex design processes. As the current generation of "computer savvy" students emerge into practice, it is predicted[10] that scripting will become much more prevalent in architectural and design methodology.

3.2.1.3.3. Visual scripting

Newer methods for developing algorithmic design do not require designers to write text code, but rather employ interface tools (such as Grasshopper for Rhino, or Bentley's Generative Components) to allow designers to work on-screen with "graph" representations of procedural instructions. These systems are often described as forms of *visual scripting*, and bypass the difficulties of syntax in code by using pictographic representations of the tools and associative logic of a design solution. Designers learn intuitively how programming components function and relate to a model by "playing and hacking" the code, displayed as a manipulable diagram.

Visual programming can be relatively limited in its scope due to the inherent constraints associated with each pre-defined tool. However the platforms are evolving, and each tools (typically) has an option for being re-defined by the user. The overall method of redefining the tools, however, is done using text based programming or scripting. As such, knowledge of scripting permits far greater levels of design control.

3.2.1.3.4. Programming

Programming languages are differentiated from "scripting" in that they are typically operating at the top level of the machine as its operating code to specifically control its behaviour. The difference between a script and a program is that a script is interpreted within a software application, whereas a program is stand-alone and executed by a machine. In computer programming, an executable program is compiled into bytecode machine language, which the computer can use directly to execute the instructions[xii]. The earliest programming "languages" predate computers, and were used; for example, to direct automated industrial machines such as Jacquard looms.

3.2.2. Programmed Design

3.4.2.1 Parametric Design

A parametric *formation* model is defined as a flexible model allowing for *topological* variation. A parametric design is such that the rules of geometry are explicit, and the resulting form is implicitly dependant on the potential of variable input. The result of a parametric definition is not a specific geometry, but the model represents a range of all possible geometries where any one "version" of the model is distinguishable from others by the explicit value of its parameters.[11]

Parametric modelling (also known as constraint modelling) has two constituent parts: a *structural* model (components and relationships), and the variable input values (parameters). Changing a relationship or component fundamentally changes the archetype, whereas changing a parameter does not.

[9] Kolarevic, B. (2001):p.17

[10] Mitchell, W. and M. McCullough. (1995)

[11] Sharples, et al. (2003)

"What is effectively being represented in the model are the decisions, or more correctly, a "transactional" model that allows a sequence of alternative decisions to be constructed, exercised and evaluated. This corresponds to the process of design at its most fundamental."[12]

The concept of parametric geometry is not new; it is based on the geometric algebra and mathematics of the antiquity. The efficient digital encoding of these principles, combined with the computers proficiency to execute complex sets of instruction is the main reason why parametric design has re-emerged design; first as shape grammars, and now as associative geometry.

"In parametric design, it is the compositional relationships and components of a particular design that are declared, not its final shape or form. By assigning different values to the parameters, different objects or configurations are created. Equations are used to describe the relationships between objects, thus defining an associative geometry."[13]

Dynamic relationships within a design allow the design to "react" to implied stimuli. The value of parametric design lies in its flexibility for exploring sets of options – a range of possibilities, for a specific composition. Parametric systems can be designed with a built-in (digital) responsiveness that automates adaptation and reconfiguration in response to changing input parameters. The importance of this logic is that it is based on a process defined by a designer but linked by the capabilities of the digital medium.

3.4.2.2 Algorithmic Design

"As of yet, designers use sketches and models to externalise a thought process, in order to provide both focus and stimulus for the development of shared ideas. The use of generative techniques that are editable promotes a higher level of awareness. It encourages all preconceptions to be challenged as they must first be formulated in explicit language."[xiii]

An algorithm is a simple instruction. Algorithmic design is therefore a set of procedural instructions for solving design problems. All procedural methods of problem solving, manual and digital, are "algorithmic" in nature, however algorithmic digital design refers specifically to programming or scripting of algorithms as equations, and their incorporation in a digital design model. This encoding of logical, conditional and parametric instructions results in the differential creation and manipulation of geometry or other digital elements.

Algorithmic design is focused on logical execution of instructions, and as such it can employ many different types of encoded analytics borrowed from other fields and sciences; for example: search and comparison heuristics to determine local maxima and minima extremes in data sets. Encoding can also be self-referential or can include higher orders of complexity; algorithms can be programmed to refine or rewrite their own instruction sets in response to iterative problem solving progress. These methods are order of complexity above parametrics, when cybernetic feedback is implemented.

As with parametric design, the main "design" task is the explicit encoding of the problem and procedural instructions to solve it. The goal for algorithmic design is a final solution to a problem (be it form finding, optimization, mathematical, or functional), but to do so in a logical, efficient and elegant manner.

3.2.2.3. Generative design

Generative design is a sub-set of algorithmic design, which applies abstract or "generative" solution strategies to design problems. Typically, the structure for generative design has:

- A design schema (the solution system and metaphor),
- a means of creating and interpreting variations (user, contextual, or other input),
- a means of selecting desirable outcomes (evaluation and interpretation code).

---

[12] Aish, R. (2006):p.42

[13] Burry, M. (1998):p.12

For certain geometric problems, specifically multi-parametric systems, there are no clear analytical solutions. In these cases generative design can be applied as an initial "form finding" application in design, and then subsequently for optimization and rationalization. Generative design systems may classified as a higher *order* of algorithmic design, meaning that they are (typically) capable of altering both their environment and/or themselves through feedback). Different strategies of generating "difference" to affect design have been invented or adopted from other disciplines.[14]

3.2.2.3.1. Random Design

A method developed in systems engineering and used in statistical analysis and scientific experiments to study the effects of one primary factor without the need to take other variables into account. Random design is a method of simplification used to control random variation in a design models.

Within an algorithm, a random function is introduced that introduces variation with every iterative cycle. By running the program repeatedly a "result field" of different *versions* is generated. An evaluation method (programmed or manual) is then used to filter and find an appropriate result. Different methods of Random Design[xiv] are chosen, dependant on the complexity and order of the problem. Random designs typically work well for large systems with many variables with low complexity, as for the method to give clearly determined results there should be few interactions between variables or influence on *structural* change in the model.

3.2.2.3.2. Image Processing Design

Digital images are highly structured two-dimensional data sets, consisting of a matrix of X and Y coordinates and a corresponding pixel value at each coordinate. The pixel data itself can be encoded with an *array* of data, typically defined as one (grey-scale) three (RGB) or four (CMYK) values that represent the colour or tone of the pixel.

Image Processing Design uses an image as the base data to generate other digital objects based on data structure. Each value of the X,Y,Pixel data is mapped to a corresponding design element, and the design is generated. If the image changes, the design program can be re-executed and the resulting design geometry updated. The simplest interpretation of such a system is a height-field or displacement map relating the tonal information of a pixel to a Z (height) coordinate to reveal a three dimensional surface.

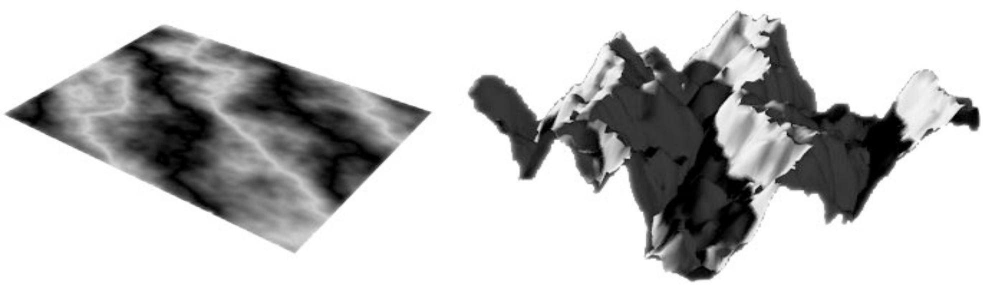


Fig.3.2.2.1.2: Displacement map height-field. Surface topology derived from grey-scale values.

The advantage of this form of generative design is the ability to manipulate the image (as input data) using image editing software tools, such as Photoshop. This process is extensively demonstrated later in this thesis in section "5.3. Control".

3.2.2.3.3. Photogrammetry

An alternate photo-derived method for capture of 3D topologies is photogrammetry. Photogrammetry uses multiple angled photographs combined with digital analysis

---

[14] Remember: architects adopt and adapt, See : "2.6. Technical Adoption"

programming to determine 3D surface geometry from many 2D images. This method results in a highly accurate representation of the actual geometry and can be very precise, but the analysis process is complex and requires large quantities of data and significant processing to return a valid topography. This process is, itself, not a design methodology, but may be used to drive context or data for generative design methods. However, if the target of a project is an abstract or re-interpreted surface (rather than 1:1 precision) then photogrammetry may be computationally inefficient and overly complex for the desired result.

3.2.2.3.4. Voronoi diagrams

Voronoi tessellation is a decompositional method for subdividing an area or volume. Subdivisions are determined by an explicit distribution of points, where each point becomes the centroid of a corresponding Voronoi cell. The shape and area of each cell are calculated such that the boundary is a function of the distance to all immediately adjoining points in that field. The simplicity of the diagram and mathematics allows it to be used for irregular but associative division, but the method can be used in three (and theoretically higher) dimensions.

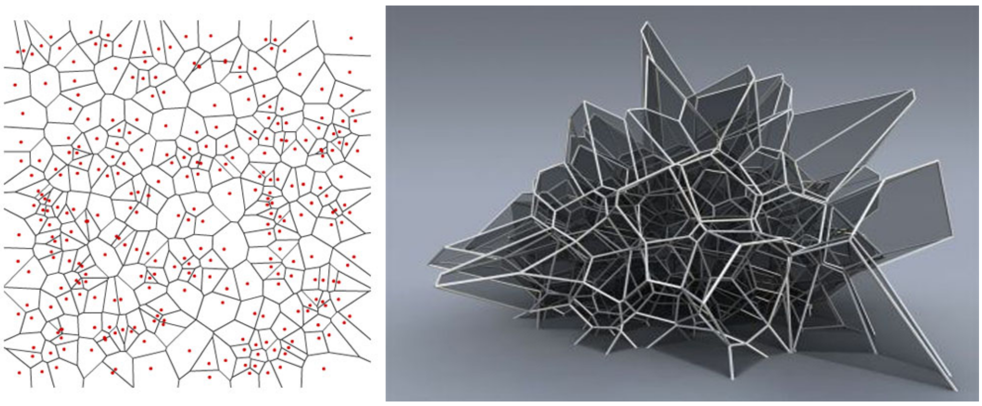


Fig.3.2.2.1.4: Voronoi Diagrams: a.) 2-D diagram, b.) 3-D conceptual model (Knauss + Oesterle)

The method is named after Georgy Voronoi, who developed the mathematical method from biological cell distribution and from mathematical packing theory. The mathematical method is used extensively in disciplines involved in mapping and statistics, but is also useful in fields of biology, chemistry and metallurgy. This method has been widely appropriated in digital art and architecture investigations.[15] Its popularity has increased to the point where some software programs have recently encoded Voronoi generators into the general toolsets, and in others CAD software external plug-in's are available to generate the subdivisions.[xv]

3.2.2.3.5. Shape Grammars

Shape Grammars are a conceptual system used for investigation of *emergent* systems in design. The method conceives a design as an experimental test field, which is populated by "shapes" encoded with specific behavioural rules and interactive potential. The system is then "animated" through iteration, and the resulting behaviours and interactions reveal possibilities of the system. Conceptually the system determines the complex transformational potential of an *emergent* system.

Shape grammars are inherently graphical languages, and as such they require a medium for display and the generation engine for interaction. Shape grammars differ from traditional languages and *Chomsky dictum* in that the development of a system may occur in parallel permitting iterative "rewriting of the statement" This permits reciprocation and geometries similar to Lindenmayer systems and fractal geometry.

---

[15] Kolarevic, B., Klinger, K. (2010):15

Because rules become complex quickly through iteration they are typically limited to constrained situations. Shape grammars systems have been explored in architectural research, and have been used to devise theoretical designs, but are most useful in limited to well-defined problems, such as room layouts, or studies of window patterns, or analysis of Palladian villas.[16]

3.2.2.3.6. Evolutionary Models

Evolutionary Models[17] or Genetic algorithms (GA) are based on biological growth systems, using search heuristic systems that follow the concept of "survival of the fittest" and mimic the process of genetic evolution. Cellular Automata and "The Game of Life" are two fundamental models for this type of algorithmic system.[18]

Genetic algorithms use the steps of: initialization, evaluation, selection, recombination and mutation as the basic rules for iterative method of systems change. A GA, as an optimization method uses the concept of "survival of the fittest" to mimic evolution. Employing specific "fitness criteria" to evaluate a "solution population", the system will evaluate a field of solutions and the worst performing solution is terminated and replace by either: a solution derived by "breeding" the best performing solutions, or with a randomly mutated solution. The process is iteratively cycled until a condition is achieved, or until equilibrium occurs.[xvi] Cellular Automata and "The Game of Life" are two models for these algorithmic systems.

Genetic algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. When used in a design program, the GA is used for optimization of desired design characteristics within a predefined algorithmic model.[xvii]

3.2.2.3.7. Boids

Complex dynamic systems composed of multiple individual agents occur regularly in nature, as with birds, fish and insects. Synchronized movement of multiple individuals, based on simple reactions creates a complex larger scale pattern called a swarm.

The digital simulation of swarming behaviour was developed in 1986 by Craig Reynolds, who identified three basic rules of conduct for each individual: Roam in the direction of the group midpoint; Move away if another agent is in close proximity; Roam in the same direction as your neighbours.[19] These rules results in an overall swarm behaviour and have been used to model accurate computer simulations. This method is a form of complex *emergence*.[20] Although computationally intensive, with contemporary computers the method can be used as a basis for optimization or creative generation of design.

3.2.2.3.8. Performative design

Performative design is the augmentation of algorithmic or generative design methods, with data feedback from simulation and evaluation. This shift, from a design model as a representation to a design model as an experimental platform makes a link between the generative processes of a design with performance analysis. In such methods performance-based simulations can directly modify geometry, and the resulting design instance is therefore a product of the performance rules for that specific application. This concept is further detailed in the following section.

---

[16] Mitchell, W.(1990)

[17] Frazer, J. (2003)

[18] See Appendix: Cellular Automata.

[19] Reynolds, C. (1987)

[20] See: "4.1. Systems Theory"

3.2.3. Digital Simulation and Evaluation.

> *"The operations exhibit behaviour that topologists track as bifurcation or even generalized catastrophe, whereby an initial set of structural stabilities produces morphogenetic behaviours and conditions that are unpredictable. This essential feature of "design language" is what makes it so powerful, and so difficult to model and formalize."*[21]

As a separate, secondary function, digital simulation and evaluation can be used for design decision support. The quality and precision of simulation systems has improved dramatically in the last decade.[22] As computer power has become more ubiquitous "lightweight" simulation and evaluation can be managed on professional CAD rated computers. For more powerful simulation and evaluation programs, "cloud" based connectivity (subscription) systems are available, which allow calculations to be processed rapidly by remote "server farms" and seamlessly communicated back to the software and user.[xviii]

When combined with evaluation tools and methods, simulation becomes a higher *order process.* Analysis software provides contextualized feedback data for design decisions, or refinement of the model (and potential iterative looping). This feedback can be employed for form-finding and geometry refinement, but evaluation data may also be used to inform other design decisions (ex: environmental systems requirements).

"A design process integrates synthesis and analysis and their permanent interaction and interrelation. The results of these cyclical processes inform the generative design work, which then loops back to further analysis."[23]

Interpretation of data from a model is an idiomatic process, with a bias on the *inferred* performance criteria. The quality of results are directly related to the quality and appropriateness of the root programming, chosen evaluation criteria, and parameters.

Criteria for simulation and evaluation can be divided into four main objectives[xix]:

- Design optimization,
- Environmental, energy, structural or other objective performance optimization,
- Construction or manufacturing optimization, and
- Occupancy performance and safety issues.

Digital evaluation tools such as Finite Element Analysis (FEA) structural analysis software or Ecotect (environmental simulation and evaluation), are regularly used by consulting specialists, and have not been widely adopted within the regular architectural profession. Each software program produces specific data formats of output with differing methods of use. The emerging challenge for designers is in knowing how to use the data constructively for intelligent design and optimization.

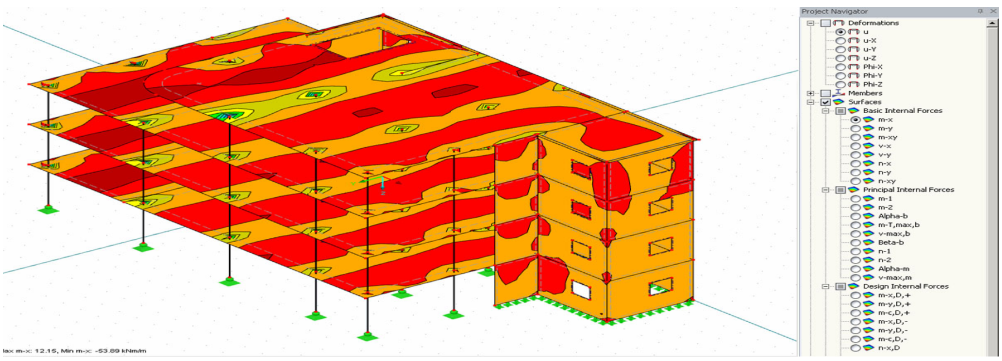


Fig. 3.2.3. Finite Element Analysis of a simple architectural test case. (RFEA modelling)

---

[21] Thorn, R. (1994)

[22] Lam, K. P., Yeang, K. (2009).

[23] Tessmann, O. (2007)

3.2.4. Digital Output

The result of digital design is data. For this data to be used further in a design or architectural project it must be interpreted for a specific purpose or context. Digital tools, both as software and hardware are also used to interpret, translate and represent data for specific purposes.

3.2.4.1. Digital Documentation

The main purpose of any architectural design method is to create the documents and instruction sets required for making or implementing of a design. All CAD software includes procedures for output of typical projection based instruction plans (plan, section, elevation, isometric, perspective). Additionally, most CAD platforms also provide tools or capabilities for higher order documentation and representation in the form of exploded views, detail views, rendered sections, level of detail views, and other forms of interpretive documentation. Advances in media[xx] infer that in the future fully detailed three-dimensional (3D) digital models may be used in place of two-dimensional (2D) plan documents as instructions for fabrication and construction of design projects.

3.2.4.2. Digital Visualization

Basic static rendering or visualization is a form of first order output. The model or digital design is interpreted using rendering or visualization software, which can represent an environment for the design including context, lighting, atmosphere effects and time. Higher orders of visualization can include the overlay of graphical information from simulation and evaluation onto a model, allowing for more in-depth understanding of the analytics. Dynamic visualizations include: animations (of the object, viewpoint, context… or all combined), animated simulations of design performance, or interactive visualizations of the design and related information.

Typically visualization is used as a representational tool for explaining and demonstrating design concepts, versions, or procedures, the advantage being that it can present design information clearly, such that complex data becomes highly digestible by professionals and non-experts alike.

Fig 3.2.4.2. Digital rendering and montage of the "Fantastic Form" Pavilion: DD+P course 2009.

3.2.4.3. Digital Analysis Data

The final type of output that should be addressed is not geometric or representational, but rather is analytic. The results from digital simulation and analysis can result in an array of data types. Typically this data is stored as either a spread-sheet matrix of calculated values, or as histogram or graph. This data may be used for technical reports or to be passed to specialists for further evaluation, however the most interesting use for this data (to this thesis) is its feedback into algorithmic design.

To accomplish a feedback loop, the data needs to be "stored" (either in memory or in a file) in a known and precisely ordered format: The data sets must be able to be parsed such that individual pieces of data can be reliably extracted for further use. This forms the basis for higher order, cyclical design iterations, and the potential for digital rationalization or optimization.

3.2.4.4. Digital Manufacturing Code

Geometric output from digital design can be used to create instruction code to drive digital fabrication machines. This type of output typically requires an additional program; such as a Computer Aided Manufacturing (CAM) program, or plug-in[xxi]. These programs are used to evaluate the design geometry, interpret it such that it is compatible with the manufacturing process[xxii], and then to "translate" the model geometry into machine instructions; and send the resulting code to the production machine. The resulting code is a list of sequential movements and coordinated machine parameter instructions, which are encoded using (one of many) standard G-code file formats.

Many CAM software packages or plug-ins are designed to optimize the production parameters associated with each type of digital fabrication. As such most CAM software is specialized for one type of fabrication or one category of fabrication machine. The parameters used to control the production output are intended to be modified to optimize machining quality, speed, and tooling efficiency, however these parameters can also be modified for qualitative, subjective and design purposes – making the CAM software part of the design process.

3.2.5. Digital Fabrication

In 2003, Professor Rob Woodbury predicted that digital fabrication would transform technology at most academic architecture programs. "*A few schools will discover some of these effects, and will be the vector by which they are spread through educational community.*"[24]

This statement has since proven to be prescient, and digital fabrication is now prevalent in most first class architecture schools. The relative ease of manipulating digital geometry allows for a high degree of geometric complexity. Traditional manufacturing methods have (over time) been optimized for Cartesian and Euclidean geometries, and are (often) not easily compatible with emerging designs featuring complex form. As a counterpoint, Computer Numerically Control (CNC) machines have no fundamental bias towards Cartesian or non-Euclidean form.

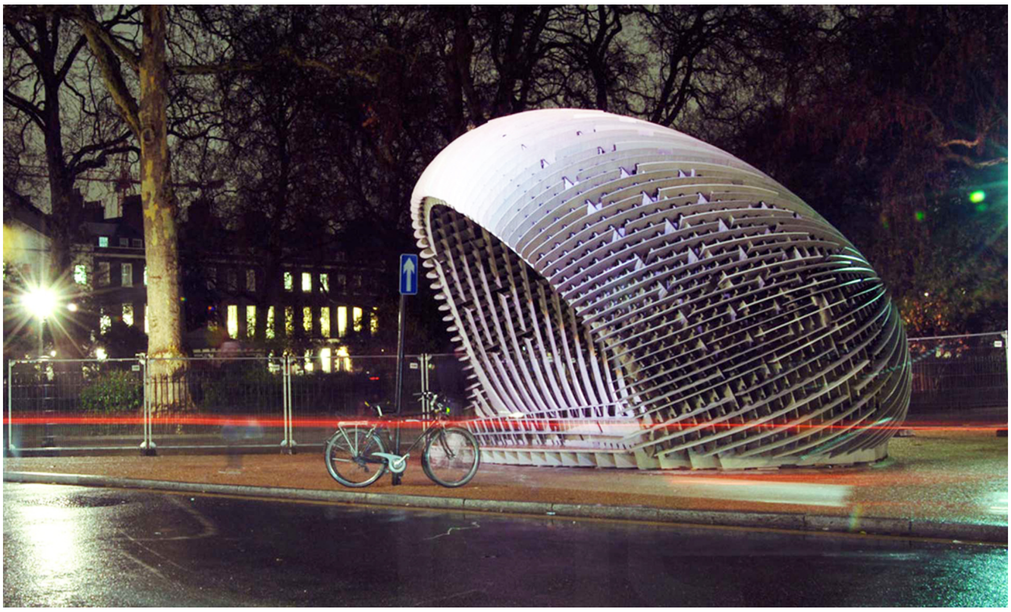


Fig 3.2.5. a.) C[space] Pavilion, Architecture Association, London: Digital Research Lab, 2010. Authors: Alan Dempsey and Alvin Huang

---

[24] Woodbury, R. *(2004) in "Fabrication"* The ACADIA 2004 Conference Proceedings

CNC machines are typically constituted by adding a digital control system to existing fabrication technologies. Digitally modulated step motors directly control the movement, speed, and position of the tooling, and instructions for movement are encoded in an NC file, directly from the digital CAD geometry. CNC controlled machines allow for very complex movement instructions with small steps and high precision. As such the geometrical constrains do not differentiate between “regular” or “complex” geometries.

A second industrialization of manufacturing and machining is now occurring.[25] Computer Aided Design and Manufacturing (CAD/CAM) is the practise of using digitally controlled fabrication machines to cut, sculpt, form, or otherwise process material into parts or components for design products. Digital fabrication has existed (within other manufacturing industries) for well over 50 years,[xxiii] however due to the *trickle down effect* it is only now becoming common for use in architectural design, manufacturing, and construction.

In recent time, there has been extensive experimentation and research conducted with digital production in architectural schools. This has been an additional motivator for the use of these machines in industrial production of architectural components and especially in pre-fabricated components and modules is becoming common.

Digital fabrication machines are available in all sizes; machines for the milling of micro-meter scaled parts for use in micro-mechanics and biology occupy the small end of the range, and large scale cutting and milling machines used to form ship hulls and airplane wing moulds are amongst the biggest CNC machines. However the process for their use is the same; develop the digital geometry in CAD software, export the geometry and process it using specialized CAM software, and transfer the processed machining code to the machine for fabrication.

Fig 3.2.5.1. b.) Large format Industrial 5-Axis Milling machine: MAKA BC570R.

3.2.5.1. Fabrication types

There are two primary categories of digital fabrication; additive fabrication and subtractive fabrication. Below is a brief description, however, these technologies have been extensively documented in other publications.[26]

3.2.5.1.1. Additive fabrication

Additive digital fabrication is the process known as 3D-printing, rapid prototyping, or desktop manufacturing. This process is the automated creation of a three-dimensional

---

[25] This is a fundamental part of the PhD thesis investigations of: Schindler, C. (2009)

[26] Kolarevic, B. (2001):*p.32-38.*

object directly from CAD geometry, through the use of programs which sections the object into discreet layers, passing the layer geometry to machines which then iteratively "prints" one layer on top of the next in sequence. The result is a stratified approximation of the intended 3D form. The resolution of the final object is dependant on the thickness of the printing media, and the precision of the machine.

Various different methods,[xxiv] sizes and materials are used in this process, and each method is typically proprietary and associated with a specific machine supplier. Descriptions of such processes are extensively outlined in publications and architectural research papers.

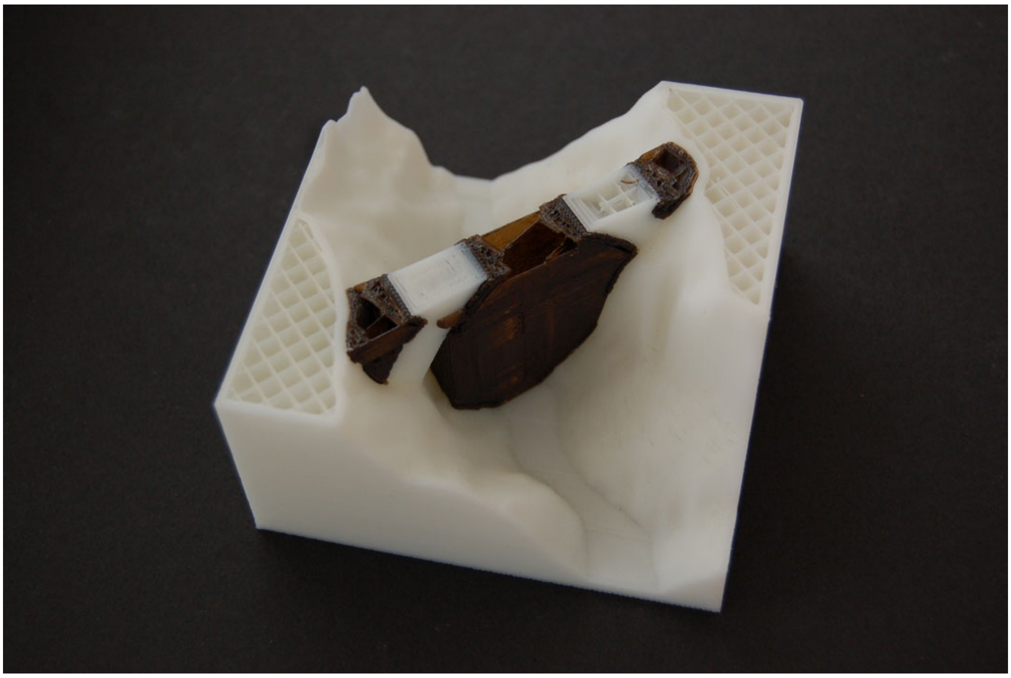


Fig. 3.2.5.1.1. Partially completed 3Dprint model using Fused Deposition Modelling (FDM). Note the interior of the model is printed in a "sparse" material saving honeycomb method. The dark brown "sacrificial" support material is to be removed later by dissolving in a water bath. (photo: M. Heynick)

3.2.5.1.2. Subtractive fabrication

Subtractive fabrication is the digital contemporary of *machining,* and is the coordinated removal of material from a solid block, so as to reveal the desired geometry. Subtractive fabrication includes cutting outline shapes from sheet material in two-dimensional (2d) processes[xxv], lathing for rotational 2.5-axis machining, and milling, or routing for three-dimensional (3D) multi-axis fabrication.

Simple CNC milling machines and laser cutters, have been popularized in architecture school workshops, and access to these tools has allowed for extensive research and projects works over the last decade. Larger format CNC machines have been extensively incorporated into existing metal and wood industries in Switzerland, however these technologies are mainly used to produce traditional constructions and structural systems. The potentials for industrial production that are possible by combining computational design with the widely available installed equipment have not yet been achieved in Swiss industry.[27]

3.2.5.1.3. Specialized integrated fabrication

A third "hybrid method" of fabrication should also be mentioned: this is the concept of specialized integrated fabrication (or Computer-integrated manufacturing). Integrated fabrication methods are a digitally controlled process chain of fabrication technologies

[27] Stotz, I. (2009):p.*22*

(additive or subtractive) and forming machines that create a *single manufacturing process* (much like an automated assembly line). Examples are: Pipe cutting and bending machines, machines that cut, stamp, and fold flat sheet metal to automatically create 3d metal parts, or a “Hundegger” machine: a woodworking machine made up of numerous CNC controlled saws, drills, and multi-axis milling heads; such that a single piece of wood can be introduced into the machine at one end, and a structurally jointed truss component emerges from the other.

Integrated fabrication processes are typically implemented in very specialized industry or for very specific product output, the working flexibility is high, but the product type flexibility is very low. Such machines are designed to achieve advantages of optimization and speed, at the expense of adaptability for other products or design.

Fig. 3.2.5.1.3. Integrated Fabrication Machine: Hundegger – composite woodworking machine.

3.2.6. Geometry Strategies

The combination of digital design with digital manufacturing creates symbiotic potential for making (and building) complex form. However the problem typically faced by a designer is not the ability to construct a design, but rather it is the ability to construct a design efficiently and within budget or other set of practical constraints. Digital tools provide possibility for *control, prediction* and *processing*, as such, their strategic application can enable an intelligent and thoughtful designer to accomplish strategic work that is more expressive, more precise, and that can be made with less waste and better construction control.

The ability to precisely cut and shape material, outside of the norms of straight lines, constant curves, or flat planes, allows for the efficient fabrication of irregular shapes. With knowledge of the available technologies and some basic geometrical strategies, most forms can be made efficiently and with minimized waste. There are six major strategies of digital forming: *sectioning, contouring, tessellating, folding and unfolding, forming, and casting*. These strategies are well documented and represented in academic and professional projects, and in existing literature and in publications.[28]

3.2.7. The Digital Chain

The *digital chain* is the concept that it is possible to create a seamless process diagram for a project, where the individual stages of work (concept, design, development, fabrication, construction, and end of life-cycle) can all be undertaken using a single progressive and coordinated set of data.

In the mass manufacturing and production industries, (where this concept has been widely adopted) specialized software is used for the industrial engineering and simulation of entire fabrication processes. The combination of digital design, digital fabrication, and the ability to

[28] See: Iwamoto, L. (2009), Kolarevic, B. (2003); Kolarevic, B., Klinger, K. (2010)

rationalize and optimize production over the many production cycles and units, allows for customized fabrication procedures. Technologies used in industry are typically controlled and optimized by MES (Manufacturing Execution Systems) or next generation Manufacturing Operations Management (MOM) control systems.[29]

The practice of Architecture does not have these same opportunities for optimization. The concept of the *digital chain* when applied to architecture extends over only one production cycle; from the instigation of a project and its brief, to the conclusion of construction, and beyond to maintenance, operation, lifecycle use, and recycling of the building upon disassembly. Although the concept of the digital chain has existed in other industries for decades, the implementation in architecture is relatively recent, and the opportunity for iterative refinement and optimization is only conceptual, not procedural.

As each architectural design is (typically) intended as a unique construction, optimization of design is limited in prototyping iterations. As such, as the complexity of a design increases, the process to produce it becomes more difficult to optimize. Architecture as a design industry is effectively a profession of *mass customization* rather than *mass production*.

The digital chain, and the use of computation tools for optimization in all stages of the process is a method to resolve this situation. By seeking refinement across the entire production process and collaboratively with each of the consulting and specialist partners (rather than only in each stage), greater potential for process efficiency, and process innovation and expression may be achieved.

> *"Key to the efficient production of 1,000 individual parts was the implementation of a continuously digital production chain from design through manufacturing. This was accomplished by a set of scripts—small programs—within CAD and CAM systems."*[30]

The primary focus of this thesis is the linkage between digital design and digitally controlled production. This "front end" of the digital chain has been replicated in our academic environment, and the use of digital design tools and computation, combined with digital fabrication and assembly create a "laboratory" for the investigation of such a chain.

3.2.8. State of the art: Technologies of note

Over the duration of this thesis investigation several other technologies of note have emerged, have been developed for architectural applications, and have matured through research and practice.

Given that the goal of this thesis includes an overview of contemporary architectural practice these technologies have been noted, and researched so as to understand their influence on emerging architectural concepts. Unfortunately the scope of investigation is not adequate to have allowed for extensive practical investigations of these technologies. However, through research and introductory experience with these technologies, adequate insight into their application and role in architecture has been attained.

The technologies of this chapter are presented in correspondence with the previous chapter, mirroring the headings of design, programming, output, and production.

3.2.8.1. Design: Building Information Modelling

Building Information Modelling (BIM) is a combination of design, simulation, analysis, and management software functions into a single platform. BIM functions with different toolsets for the different members of a design team, but the background programming assembles all the information into a common model. The model of a building's physical components is constructed digitally, and can be used for simulation and analysis, while simultaneously (and inextricably) all components linked to a report-generating database.

[29] Kelly, K. (2012).

[30] Scheurer, F. (2009)

BIM software is modular, and can be scaled for individual projects to include design tools, consultant integrators, simulation and analysis. Further down the digital chain it can also include CAM output, simulators for robotic production, construction, building management, and in the creation of spread-sheets of materiality for eventual "end of service" building recycling. One of the key cited features of BIM is the ability to generate 4D (time based) simulations of projects and their construction assembly.[31]

When used on large planning and construction projects, BIM allows for strong coordination between professionals and their interaction with the data set as it moves along the digital chain. The software can be programmed to monitor work and progress on the model, and using various tools, BIM can be programmed to identify conflicts, manage interactions, and control data flow within the larger team.

There is much professional discussion about standards, methods, and impact of BIM on professional working methods. Although in some markets, the use of BIM as a required format for submission of permit documents is causing adoption, there is still a perception that it requires higher time investment for modelling and managing projects. This resistance will likely remain until the understanding of BIM has graduated beyond the notion of a type of enhanced CAD documentation software to strategic knowledge sharing platform and project facilitation and management system.[32]

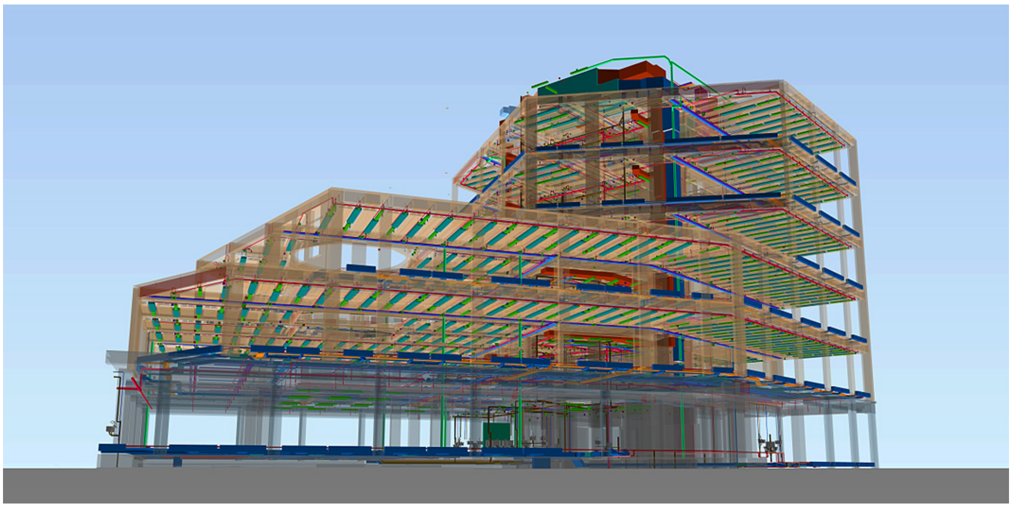


Fig. 3.2.8.1. Building Information Model (BIM) – showing structure (timber + concrete) and services. SITRA Office: Helsinki, Finland; Sauerbruch Hutton Architects. (Model: Arup)

3.2.8.2. Programming: Agent-based modelling

Agent-based modelling (ABM) is an advanced order of algorithmic design. Autonomous agents are representational objects that are programmed with complex behaviours. These "agents" can then be introduced into a model simulation, and their behaviour and interactions are recorded as an analytical method. The power of this method is achieved when multiple agents are employed to create highly complex situations of self interaction, such as is seen in realms of fluid dynamics, biological swarming behaviours, or molecular physics. ABM is an analytic method, and is used to model and analyse probability in highly complex systems.[xxvi]

For design and architecture, agents can be programmed to represent simplified person behaviour. Human behaviour is (for the most part) too complex to convert to an algorithm; however, in moments of stress or panic, the fundamental psychology becomes very predictable and easy to program. For architectural purposes, Multi-agent modelling

[31] Eastman, C. (2009)

[32] From: Seletsky, P. (2005)

is a tool that can be used for predicting emergency situations in buildings. The analogue is releasing "people" into a building proposal, applying a stimulus for action, and seeing how they react. These methods are used for emergency evacuation simulation, fire and smoke simulation, as well as general design of person flow through very large projects such as stadiums and transportation stations.

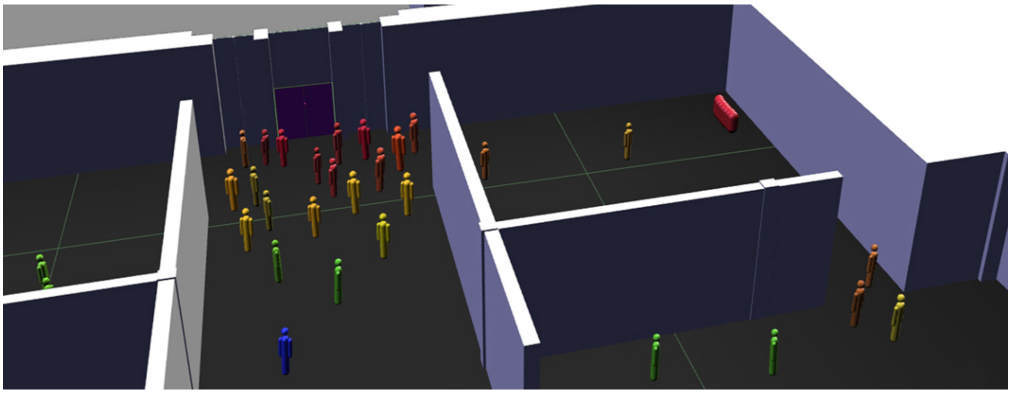


Fig 3.2.8.2. Evacuation Simulation using autonomous digital agents: Massive Insight Software

3.2.8.3. Output: Augmented reality

Augmented Reality (AR) is the superimposition of digitally mediated information into a real-time, direct or indirect view of a real-world environment.

Indirect AR, provides contextually appropriate geo-specific information to a portable device such that it enhances the users ability to negotiate that specific place. This type of indirect AR is already in limited use in smart phones, tablets, and portable computers.

Direct AR is typically achieved through the use of *wearable computing* and a head mounted display. The system recognizes the real world view and synchronizes and implies contextual (or other) information into that view, thereby enhancing one's current perception with contextually specific information.

In advanced iterations of AR technology the digital contextual information may be interactive and manipulable. This system differs from *virtual reality* in that the VR environment is a synthetic context, whereas AR is location and real-time specific.

Figure 3.2.8.3. Life Clipper: Augmented Reality superimposition of proposed landscaping at Basel port

For design and architectural purposes, AR can be used to give viewers a 1:1 sense of proposed projects, technologically mediated into real context. *Life Clipper*[xxvii] *a research project at the FHNW,* permits the superimposition of digital model geometry into the physical view of specific places. The project; to visualize and contextualize architectural proposals for the Novartis Campus in the city of Basel, allows the viewer to move (physically) in the Novartis Campus area, and through the head mounted display, see representations of proposed projects mapped into the perspective view.

The precision of synchronization of digital data with real worldview is the biggest challenge of this technology. However, as this is a technological challenge, it is fully expected that as the technology evolves the "lag-rate", graphics processing abilities, and portability of the equipment will dramatically improve.

3.2.8.4. Production: Industrial Robotics

Industrial robotics are large CNC controlled "arms" equipped with exchangeable tool heads, and are typically employed in large mass production industries.[xxviii] The inherent adaptability of movement and flexibility of tooling means that robotics are less constrained than function specific CNC fabrication machines, however this is achieved at the expense of precision (when compared to fixed and ridged CNC machines) and ease of programing. Fabrication constraints of robotics are configuration, size, and speed, where due to the wide range of possible motion, correspondingly large safety zones are required around the machines.

The inherent advantages of robotics, compared to contemporary CNC machines, lies in the wide range of movement (multiple axis and multiple elbows), and the flexibility and adaptability of separating the tooling from the movement. Through this ability to change the working function at the "end" of the robotic arm, the robot becomes a "multi-tool" that is actuated by the robotic movement of the arm.

The architectural and design applications of robotics have been especially prolific in resent research, projects, and publications. Robotics are being employed for investigative design in many architectural schools, and also in professional consulting and industry.

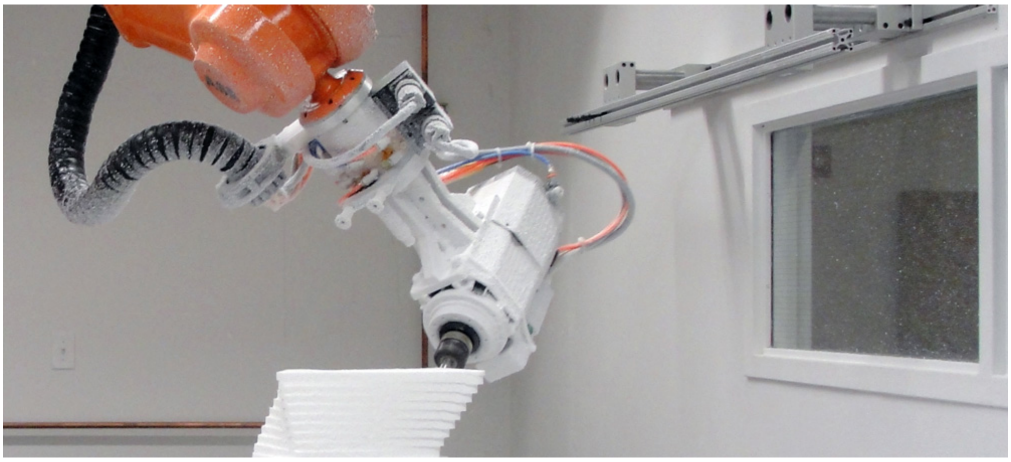


Fig.3.2.8.4: Robotic foam milling: Digital Fabrication Lab at Carnegie Mellon University.

3.2.9. Technology Future

"Technology is a fickle master, those who are not sensitive to its trends are condemned to obsolescence."[xxix] Although the trickle-down theory is a relatively clear and consistent indication of new and emerging technologies in architecture, it is not comprehensively complete. In technology predictions, just as with innovation, there is always the possibility of a radical innovation that no-one saw coming. Although architecture, as a "second level adopter" of technology, is somewhat insulated from rapid change, … there are no guarantees of an unpredictable future.

In his (now extremely interesting) book: *"Architecture 2000: Predictions and Methods"*[33], written in 1971, architect and theorist, Charles Jenks, charts predictions about the evolution

[33] Jencks, C. (1971)

of architecture. They include such realised potentials as robotics, industrial fabrication, and computer aided design, but the predictions fundamentally lack any concept of the Internet, the digital pervasiveness of information, digital communications, and the dramatic effect that they have had on contemporary society and civilization. The architecture, and urbanity of today may not look very different from that of 1971, but the invisible and globalizing effects of pervasive digital technologies are a radical change to how society functions.

The technology investigated in this thesis is technology of the present, the techniques developed in experimentation are techniques for production tomorrow, …but for the long-term future, both the author, and Charles Jencks, can only make informed predictions.

3.3. Architectural Technology

> *"The "Albertian paradigm" has defined the architectural profession in the West, and to this day still underpins the global practice of architecture. In the modern, humanist tradition architects are expected to design objects without making them, and builders are expected to carry out the design notations they received without changing them. The separation between design and building limits the realm of buildable forms to those forms that can be geometrically notated, and measured in drawing. In turn, the architect's authorial role depends on the identical translation of architectural notations into building: as Alberti first stated, all changes in design that are not "authorized" by the designer should be considered as errors. The industrial revolution, and the mechanization of construction technologies that ensued, further validated and corroborated the importance and extent of this notational and authorial way of building. The digital turn (the shift from mechanical to digital technologies) has drastically reversed this trend. As digital tools can be used to design and fabricate at the same time, CAD-CAM technologies have already started to bridge the gap between conceivers and makers."*[34] *M. Carpo*

Architecture, like all professions, adapts to its technological context. New and evolving technologies drive innovation in practice, providing expanded capabilities for work and production, but also providing new insights and perspectives on existing problems, expanding the scope of problem solving, and contribute capabilities to take on problems in new unforeseen ways.

3.3.1. Computers in Design

The computer is a tool for the amalgamation, manipulation, and development of information. Computers do not create information; this is the responsibility of the user, in our case the designer. The first steps towards the adoption of computation into design were early in the history of computation; in using the computers to solve abstract geometric and analytical problems. This was initially done using "punch-cards" for input and output, however, technology evolves, and hardware and software that included abilities for representation and manipulation of geometry on a computer screen were invented in the early 1960's.[xxx]

The evolution of computer hardware, from mainframe to personal computer, and the related exponential increase in computing power (and reciprocal decrease in cost and size) has brought corresponding advances in digital tools. With the pervasive use of computers in professional offices, the dominant medium for architectural work is now digital.

3.3.1.1. Technology in Practice

Architecture is the "*child of practice and theory*,"[35] and yet because of this it is also in a continuous state of transformation. There is an intimate and complex relationship between theory and praxis such that the two issues are producing and affecting

[34] Carpo, M. (2008):127

[35] Vitruvius (30b.c.) *The Ten Books on Architecture*, Dover:p.5

architectural knowledge concurrently. This simultaneous symbiosis and antagonism is an indispensable condition that creates a tension; one of wanting to instil an intelligence and elegance, while at the same time needing to address reality and functional design criteria.

Technology and its use in architecture have a similar self-referential result. In empowering the abilities of the user to accomplish work. Technology has potential to change the way that work is conceived, which reveals new opportunities for the application of technology. If explained with the analogy of physical tools, the production capabilities of a tool at hand will influence the designer, and thusly influences the design to be conceived[xxxi]. In the case that the tool is an "augmenter of information processing" (such as is the case with computers), then the tool will affect the *conceptual* methodologies that are used to design.

The implementation of new technology however carries risks, and when dealing with professional commissions risk is to be avoided. Computational design therefore is often heavily constrained within proven methodologies, and the scope of a work is singular in focus so as to limit potential problems within the greater design-production workflow. Otherwise, computation tools in design are primarily used for analysis of explicitly quantifiable parameters, or for visualizations and simulations, all in aid of facilitating, justifying or speeding design decisions.

There is an interesting irony that the architects who are comfortable and experienced in the leading edge technologies (and specifically advanced computing), are typically young, fresh graduates with minimal professional experience. This situation disjoints the traditionally vertical "master / apprentice" relationship in many practices, and shifts control away from experience and gives it to those with the skills of advanced tools.

For the young practitioners, the result of this (should they choose to practice away from a "master") is that the work achieved occurs more often at the conceptual level. Even though their technical skills have been developed to work with the tools that can handle large scale complexity, their architectural experience doesn't qualify them for access to such projects.

This reality often invokes a process of self-development for many younger practitioners. Small-scale "demonstration" projects, collaborations, and consultancy are all used to advance the architectural knowledge required to graduate up to larger scale projects, this creates a new path of architectural development for a technologically mediated practice. This mode of practice is only now approaching maturity, such that large complex projects are beginning to emerge from these early digital adopters[36]. This is a first and notable indication of the current state of technology and its use in the architectural professions.

3.3.1.2. Architecture as information

"Most architects do not make buildings – they make information for buildings. They turn ideas into drawings, models, texts and data, where many results inform the production of buildings and others do not."[37]

Innovations affecting design and production can be categorized as either physical innovation; affecting fabrication and the physical manifestation of a design, or the technologies are informational; affecting the representation of concepts and ideas, the manipulation of definition data, or the evaluated knowledge and expectations for a design.

Increasingly architects have become isolated from the acts of building and construction, and are progressively engaged with issues of design, style, and the management of the information that defines a project. The development of the personal computer, and its gradual adoption into professional practice in the early 1990's was the beginning of a shift in medium for architecture, from analogue to digital, and a transition to using a tool that augments the ability to deal with the management of information.

[36] Sharples, et al. (2003):p.53.

[37] Sheil,B. (2005): pg.5

3.3.1.3. Disruption of architectural practice

The implementation of the computer has had a fundamentally *disruptive*[xxxii] affect on the profession of architecture; the democratization of practice.

Before the use of digital tools, for offices to undertake large and profitable projects, the office itself needed to have a corresponding size of manpower to allow for adequate production capacity. This manpower was distributed between design (architects and engineers) and production personnel (draftsmen).

When technology, and specifically computer aided design was first introduced, only the largest firms could afford its implementation. This crated an imbalance of competition with smaller or less profitable firms; on one side there was the advantage of assisted production capability, but it came only after the great investment of capital, time and expertise to implement it. However, given the evolution of the technology, there has been a substantial and subsequent democratization of practice. As the cost of implementing full functionality CAD platforms decreased, their deployment increased to the point where they are now ubiquitous. This, in turn, has led to a dramatic reduction in the number of draftsmen employed; typically replaced by designers who manipulate and conduct their own production drawing on the computer.[38]

3.3.1.4. Disappearance of the draftsman

This reduction in the role of the draft-person has had two effects:

The first is the reduction in average office size compared with the ability for production. The computer and appropriate digital tools has substantially increased the capacity for design and production, and the work is accomplished as one comprehensive process rather than in divided parts and clear delegation of labour and authority.

The second effect of the computers replacement of personnel may be less obvious; it is that the historic positions of designer and draftsperson were a symbiosis, a feedback loop that enabled creative design and the output of clear and precise production documents. The designer was an expert in the development of content, and the draftsperson was an expert in the translation of design into instruction documents. Both professionals understood construction, but in different ways, and both contributed to the project through reflective and rhetorical discourse. The training of a draftsperson made them an expert on issues of representation, geometry, modelling, and detailing for construction. The content of their "expertise" was not just rules and data, but was also a developed intuition and experience which could be brought back to subsequent projects. The ability for the design and production staff to enter into discourse, to have multiple levels of reflection on a design has been (somewhat) removed from current digital practice. Computer systems, no matter how well programmed, do not engage in reflective discussion in the same manner of two experts.

Geometry, modelling, drawing, and production output rules have all been encoded into CAD programs. These digital tools simplify the workflow for designers, however, the requirement of basic knowledge and experience, the understanding of how to enact these issues, has also been made the responsibility of the designer. The result of this seems to be a stratification of designers, those who are good at creative and conceptive design, those who know how to deal with geometry, those who know how to deal with the tools, …and those who expertly deal with them all.

3.3.1.5. Emergence of the geometry consultant

When a projects geometric complexity reaches a critical level, the ability of the tools, and their lack of informative feedback becomes a constraint to a designer who does not understand the fundaments of mathematics and projective geometry. This situation has led to the evolution of the role of the draftsperson, a "new" profession within the design

---

[38] Mraz, S.J. (2009)

practice: the "geometry consultant"[39]. This new role re-envisions the expertise of the draftsperson within the scope of the digital medium. This role has expertise in geometry, programming, data structures, a thorough knowledge of digital fabrication methods, and an overview of their use with materials and construction systems.

3.3.2. Technology in Practice

In current architectural practice there exists a wide range of strategies for implementation of digital tools into professional practice. These strategies can be categorized into three generalized categories based on the level of integration of technology into the regular design and production processes: Architecture practice, Architectural consultancy, and External consultancy.[xxxiii]

3.3.2.1. Architectural practice

3.3.2.1.1. Comprehensive users

Comprehensive technology users are defined as architectural practices that engage technology in the production of their architectural projects, but where the technology is not a primary driver in the overall design strategies presented; technology is responsive to conceptual design intentions. The practices use digital tools at a high level of expertise, but for complex computational needs, external consultancy is sought.[xxxiv]

3.3.2.1.2. Professional research and development groups

Several large architectural practices have developed specialized internal groups specifically devoted to developing the use of emerging technologies in projects and methodologies. These groups are typically independent teams that cooperate and guide designers during development. In many cases the technologies used drive the design process, and are a primary factor in the resulting product.[40]

3.3.2.1.3. Integrated offices

Integrated offices are architectural firms that have dedicated their working methodology to include direct feedback from production and construction in the design method. Typically the architects themselves are directly involved in the design, production and construction processes. Integrated offices typically are engaged in "design build" and have their own production machines for small scale production, and strong working collaborations with large-scale industry for larger projects[41].

3.3.2.2. Architectural Consultancy

In situations and projects where the "in office" skills of geometry, computation, or other specific requirements are not adequate, there are alternate consulting sources for expertise.

3.3.2.2.1. Engineering offices

Large scale and complex projects often require significant resources and integration with other technical implementation. Large professional engineering firms are also now investing in digital design and production support groups.

3.3.2.2.2. Geometry or specialized consultancy

Specialized consultancy conduct specific research for design or production issues. These working groups can be classified into two types: Geometry consultants, responsible for design, fabrication, and construction issues, and specialty consultant responsible for other areas of expertise related to architectural performance or function.

3.3.2.3. External Consultancy

3.3.2.3.1. Fabrication services

Advanced fabrication service-providers and product suppliers offer digital consultancy for clients. This consultancy is an evolution of the "shop drawing" model, and is directly used

---

[39] From: Scheurer, F. (2009)

[40] From: Whitehead, H., Aish, F. (2004)

[41] From: Sharples, et al. (2003)

to streamline and optimize designs for the specific equipment or technical capacities using parametric techniques. These services use in-house programming specific to the products or fabrication capabilities. Such services are offered to augment the commercial appeal of the business, but it is also a method for altering the contract model, to integrate the fabricator into the project team, and at an earlier point in the production phases.

3.3.2.3.2. Hybrid research groups

Hybrid research groups are entities that are a collaboration of players and are typically associated with universities or external research institutes. These groups engage in consultancy with professional work as a method to verify and authenticate novel or prototypical working methods, concepts, or technologies. The collaboration benefits are expertise and breadth of knowledge for the office, and access to "proof of concept" real projects (with the likelihood of 1:1 realization) for the academics.

3.3.3. Technology motivators

Architecture as a practice does not exist in a stable and static paradigm; it must innovate to meet changing expectations and changing context. The current, most significant, motivator of innovation is environmental sustainability and the ecological impact of design and urbanism. Architecture has a moral responsibility to address the urgency of global warming, however as backup, new performative regulations ensure that innovation is required.

The priority concern of ecological issues related to reduce or eliminate CO^2 and greenhouse gas production. The measure of *exergy*[42] and its comprehensive focus on balancing energy, resources, performance, and requirements provides an initial basis for design decisions. Digital performance simulation and evaluation combined with knowledge intelligent sustainable design methods, appropriate and location sensitive materiality, and energy and resource management technologies are all important in contemporary architectural design.

Technologies will be vital to managing these issues in logical, but still creative and responsive manners. This thesis proposes that digital technologies will play a large role in the resolution of these issues. New materials, technologies, and processes developed specifically for architecture are already improving performance efficiencies in construction. Significant potentials for optimization occur when these factors are integrated into a digital chain.[xxxv]

3.3.4. Architecture Future

The diversity of architectural practices implies that most offices can be situated on the productivity graph of architecture, between the slope of the "vanguard architects" (early adopters) and the continuous slope of traditional practice. However, the skills of dealing with technology, and by extension their links in the digital chain are becoming more important. Informational complexity is increasing in the architectural practice, emerging codes and regulations now require a minimum of digital proficiency. With a persistent supply of young technologically savvy practitioners, every competitive professional needs to implement an appropriate strategy for technological evolution in practice.

As the use of technology becomes more sophisticated, the interaction between designers and technology becomes less clearly defined. In a simple project, the designer uses a specific tool to resolve a specific a task; the return is a clear solution. As more variables, processes, and technologies are engaged for complex problems, the solutions also have potential to be complex. As technology becomes less precisely delineated, its role also becomes fuzzy. What is driving the final solution? Is it the ability of the algorithm to calculate the input from the designer, or is it actually the ability to interpret the output by the designer?

The understanding of technology by the practitioner improves over iterations in a project, and the technology itself is refined over iterations of projects in a practice. As this evolution occurs, its use becomes predictable. At a certain point of familiarity, the technology that was

---

[42] See: Meggers, F.(2010) in: Ruby, I +A. (eds). (2010):p.20

originally a novel independent tool becomes an invisible part of an established process, and at that point, perhaps the division between designer and technology becomes irrelevant?

3.4. Material Technology

> *"This is the craftsman's proper conscious domain; all his or her efforts to do good quality work depend on curiosity about the material at hand.[43]"*
>
> – Richard Sennett

Digital technologies have been presented thus far in relation to their conceptual and physical influence design. In both theory and practice, architectural influences extend far beyond these issues, and resultantly this investigation must address other influential, and non-digital topics that have a significant connection between design and technology.

"Material" is defined as *matter that has been organized for specific purpose*. As such material is simultaneously both "substance" and also design. "Materiality" may be understood as an explicit organization, a *tropic reaction* to forces that are implied upon it. These forces need not be physical, but may be conceptual and abstract. In understanding them material development can be optimized so as to respond to specific needs of a task or design.

As conceptual (yet immaterial) digital design emerges, the question of how the project will be realized generates a series of opportunities. Designers approach this transition differently if equipped with a critical understanding of fabrication and materials. Materiality in design has a clear influence on the quality of the resulting product. Only with a clear knowledge of craftsmanship and understanding of interactions between material and method, will a designer have confidence (*pathos*) in a design[44].

The range of history reviewed for this thesis, mostly focused on the invention of materials as catalysts for other inventions, and in most cases the texts were documentations to preserve date and inventor details.[45] However the evolution of material science inventions shows a clear relationship to the development of technology, as well as the bigger story of the evolution of design and its further relation to civilization.

3.4.1. Construction materials

The typical palate of construction materials has changed very little over the last century. The majority of built projects still use materials that fit into the classification of the elemental construction materials taken first from the construction guilds, and then formalized in categorizations at the Bauhaus: Stone (mineral solid), Aggregate (mineral compositional: clay, concrete, brick, tile, plaster, coatings…), Glass (mineral vitreous), Metals, Wood (Fibrous solid), Textile (Fibrous mesh), and Colour (pigment, paint, finishing).[46]

The dominance of these materials was strengthened by the newfound industrial capability to mass manufacture and deploy them in the industrial revolution. With an exponential rise in consumption and use, came additional engineering knowledge of calculating and prediction. This combination of production methods and knowledge brought radical innovation in architecture and construction, further amplifying the feedback loop of technology and design. To this day, there has only been iteratively innovation on these technologies; we continue to build using these same materials, methods of assembly, and similar technologies. Although science and engineering have radically improved, architecture is still built with bricks and mortar, wood and stone, and steel and glass.

---

[43] Sennett, R. (2010):p.120

[44] Sennett, R. (2010):p.120

[45] Ex: Yeomans, D. (1997); Peters, T.F. (1996).

[46] Wingler, H.A. (1969)

3.4.2. Materials Innovation

3.4.2.1 Material Science

Material science has traditionally been an area of academic and scientific investigation with a fundamentally objective approach. Architects and designers now look to other industries to *adopt and adapt* materials innovations. A brief overview of materials innovation reveals that this condition is changing, through access to digital design and digital production systems, the scale of design is widening, and as such designers can become material designers as well.

3.4.2.1.1. Synthetics

Since the industrial revolution, the area of most significant invention in materials has been in synthetics. The discovery of the vulcanization[xxxvi] led to both the development of modern plastics, but also led to significant advances of chemistry and molecular science. The contemporary scientific ability to tailor specific material properties, by manipulating molecular synthesis has resulted in a vast array of materials with explicit properties.

3.4.2.1.2. Composites

Composites combine multiple materials to create heterogeneous compositions with specifically tuned characteristics. Found in both nature and industry, composites are "designed" as intentional scientific synthesis or natural and organic *tropisms*. Composites are used extensively in industries, including aerospace and automotive with emphasis on structural strength and weight savings. Architecture has now benefited from similar material applications[xxxvii]. Composites heterogeneities can occur at many scales. Most familiar composites are macro scale, however biological and synthetic composites are also formulated at the micro-level resulting in materials with variable and non-linear characteristic responses.

3.4.2.1.3. 3D-printed composites

Advances in 3D-printing techniques and molecular structuring[xxxviii] are at the forefront of contemporary fabrication technologies and allow for digital design of small-scale composite materials. By using multiple printing materials, with different performative characteristics, complex 3D structures can be printed with specific three-dimensional geometric configurations.[xxxix] The combination of soft, hard, flexible, conductive or non-conductive materials allows for highly performative composite structures.[47]

3.4.2.1.4. Bio-materials

Nature is by definition sustainable; repurposing natural methods, structures, and systems is the field of Biomimetics. Nature (typically) operates in a mode of conservation of energy; organic systems respond to stimuli and stress by modification of shape and material properties before the additional material. With increasingly precise digital simulation, evaluation, and production technologies, conservation of material (and therefore energy) as a strategy can be scaled into structures, skins, and systems of architecture.

Biomimetic principles have inspired the development of advanced performative materials. Examples include: synthetic spider web, carbon nanotube conductors, heat shedding silicon membranes, "breathable" membranes, starch based biodegradable plastics, …and many others.

3.4.2.1.5. Re-engineered materials

Revisiting traditional materials with new treatment and processes knowledge results in their re-engineering and the creation of new materials from traditional sources. Significant innovation is occurring in the glass, metal, timber, and other natural fibre material industries. Examples: engineered timber, "Gorilla" chemically hardened and elastically flexible glass, composite bamboo, natural fibre reinforced plastics, cellulose composites, pressed cellulose, metal foams, hydrophilic wood… amongst others.

[47] Oxman, N. (2010)

3.4.2.2. Material design

The changing nature of materials directly affect the approaches that designer take, and their expectations for material performance. As the substance of architecture evolves new possibilities for design and production also emerge, however any new understanding is bi-directional. With new production technologies, designers are now actively participating and engaging in the synthesis of materials[48]. This ability to specifically define required properties for design, performative, or aesthetic traits in a project changes the relationship between process and production, and between designer and fabricator.

3.4.3. Material Future

Richard Sennett in his seminal review of *craftsmanship*[49] proposes that interest in materials and its role in innovation relates to the psychological associations of experience.

> *"People invest thought into things they can change, and as such thinking revolves around three key issues: metamorphosis, presence, and anthropomorphosis."*[50]

Sennett goes on to explain each term: *Metamorphosis* is a direct change in a procedure, technique, or a material. *Presence* is the maker's influence, which they impart into the object (ex: conscious decisions of materiality), which then affect the user. *Anthropomorphosis* is the situation that human qualities are attributed into a design or raw material; such as wood being described as "warm or friendly", and steel or concrete as "cold and hostile".

From this view it is evident that material meaning and relevance lies in issues of personal tradition, experience, and vernacular association. Synthetics of all types are commonly used in architectural design, but typically in technical applications, not as primary haptic materials.

This finding is reinforced in the book *American Plastic: A Cultural History*[51], which questions why the general public has accepted plastic in so many artefacts of everyday life, but does not accept it as a valued building material in houses and architecture?[52] In determining the impact of new technologies on architecture, the role of public perception and their willingness to engage with new technology in their daily lives cannot be overlooked.

Therein lies a fundamental issue in the study of technology and architecture: Popular public response to architecture is tempered by vernacular experience, nostalgia, and a reverence for historical permanence[xl], all of which favour the known rather than the novel. If architecture as a profession is expected to function at the "cutting edge" of technology; is expected to engage the latest technologies and methods to reduce energy and environmental impact; is bound by ever evolving regulation in the form of building safety and security codes; and is expected to engage in a form of "material honesty", then how should the architect manage the public reverence for traditional materials against innovation.

The answer lies in technological innovation, but also in the intelligence, sensitivity, and knowledge of the architect, and their skill in combining them all using appropriate tools.

We are currently in an age of rapid growth in material science. The change that is emerging is the rise of customized, designed, performative materials; materials that interact in an active manner with their environment. Whether this is through chemical reaction, physical change of form, or through other characteristics such as bioluminescence or acoustic attenuation, materials are ceasing to be simple mass, employed for structure and containment. The deployment of "smart materials" in industrial applications is already underway, so any architect with a knowledge of the *trickle-down theory* should already be preparing for the re-contextualization of smart materials for architecture, and the changes that this will bring.[xli]

---

[48] Oxman, N. (2010); Bourlier, E. et al. (2002); Soar, R., Andreen, D. (2012)

[49] Sennett, R. (2010)

[50] Sennett, R. (2010) :*p.120*

[51] Meikle, J.L. (1997).

[52] Meikle, J.L. (1997)

3.5. Construction Technology

"Build, don't talk!"[53] - Mies van derRhoe

As with material science, the act of "making" is, part of the architectural process, but also outside of the contemporary control of the architect.

The process of construction, and the development, management, and coordination of the process for a specific project are a design method unto itself. The integration of design, material, technical, and control issues are a complex and information intense process, and there already exist multiple digital toolsets to assist with this (including both logistics management software, and Building Information Models: BIM).

Industrial fabrication processes that focus on mass production are designed for maximal optimization, and are typically controlled by MES (Manufacturing Execution Systrems) or the more advanced Manufacturing Operations Management (MOM) control software packages. These softwarea packages monitor and control a factory or industrial "line", and can be integrated with CAD/CAM processes for variations in product output. The "state of the art" for each industry is an extension of the afore mentioned methods of fabrication, with the goals of reducing tooling, fabrication time, and (sometimes) material wastage.

Such industrial tools and their purpose translate well to construction, where the most analogous software is BIM. The advantages of predictive simulation and analysis, project monitoring, and management of complexity, allows the *construction manager* to deal with the project in a proactive rather than reactive manner. Addington and Schodek assert that these programs are not intended to engender innovation, rather, they are practical templates for communication between architects, fabricators, suppliers, and general contractors. [54]

When using BIM for project management the advantages are further enhanced through animated simulation. The results of this are visualizations of workflow and the ability to see, analyse, and compensate for problems "on the fly". The use of digital tools in project management can achieve efficiencies, both in production (labour, materials, waste, and energy), but also in time; and in construction, time is money.

3.5.1. Assembly

By intelligently engaging the different stages of the digital chain construction can be facilitated. Potential improvements come at both the level of the components, and also in how they are assembled. By incorporating a designed logic of assembly, one that corresponds to the strategic management and control system, efficiencies can be achieved.

Project organization is essentially a very large and complex puzzle. The complexity of pieces, order of assembly, and management of unforeseen site issues are the parameters that need to be resolved. If design and production can be used to intelligently mitigate these issues before arrival at site, then the assembly may be optimized. There are a number of strategies involving digital tools and the digital chain to do this. Of note are:

- The use of digital control systems and specialized labelling (symbols, barcodes, RFID) for connections (electronically confirmed by connection to a BIM or construction database).
- The concept and design of customized connections; unique designed connections at each assembly point, such that when assembled there is only one possible correct way to join the pieces together.

The inclusion of robotics, as an extension of the digital chain into digitally assisted assembly, is a focus of much research and investigation by other groups. The implications of these

---

[53] Schulze, F. (1995):p.120

[54] Addington, M., Schodek, D. (2005).:p. 26.

automated fabrication techniques to the future of architecture and construction is not clear as of yet, but what is clear is the complexity and capabilities that they bring to "making". This is an emerging field of research, not investigated in this thesis, however the implications and some findings are included in the discussion of this thesis.[55]

The design of assembly, and the intelligent use of digital tools with the production chain can have significant effect on both the speed of construction, but also (with care!) the tolerances, quality, and finish or an architectural project.

3.5.2. Precision

A significant trait of digital technology is the precision to which a design can be formulated. With the use of digital fabrication, this precision is transferred along the chain to the production of components. This raises the issue of compatibility of tolerances.

In the controlled conditions of a design office or CNC workshop, tolerances are limited only by the digital design, and by the physical tolerance of the machines and material being used.[xlii] Construction tolerances site are, however, are significantly different. The unpredictability of site conditions and any irregularities, and the "imprecision" of manual labour creates inconsistency of tolerances. If pieces are made to fit together too tightly, they may not have adequate flexibility to accommodate the small variations imposed due to site issues, if they are tool loose the quality of construction is poor. This is a significant issue within a digital chain.

Determinations for tolerances are made based on the expectations of design (quality, fit, geometry, performance), the materiality, the fabrication and assembly processes, how the production and design are conceived as a system, and finally the expertise and experience of the fabrication team. Digital modelling, simulation, and BIM tools can all assist with these issues, but it is the architect and construction supervisors who are ultimately responsible.

3.5.3. Precision of making

Recent trends in construction, and specifically large and complex projects, show a movement towards *prefabrication* and *"chunk" fabrication* and assembly methods.

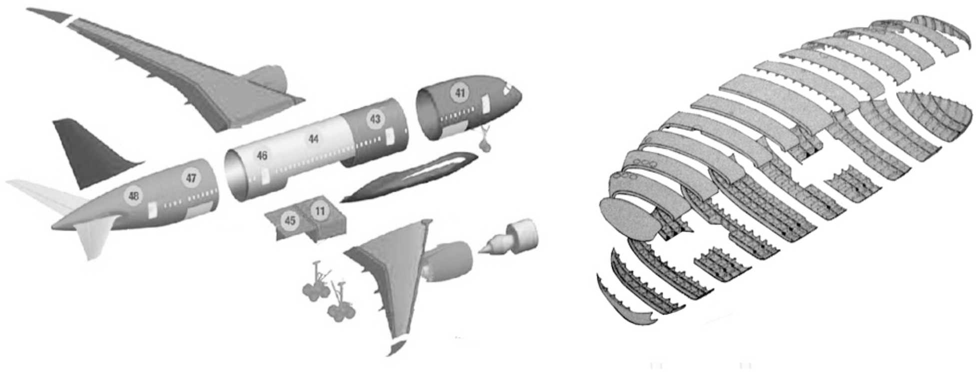


Fig.3.5.3: Chunk assembly concept: a]. Boeing 787. b.] Natwest Media Centre, Future Systems Architects

Prefabrication is the manufacturing of entire projects, components, or systems in an industrial setting, and then the subsequent packaging, transporting, and rapid installation of the components on-site. The potentials for control and precision of fabricating components in an industrial setting (factory) are a significant advantage. The ability to prepare each component in all of its complexity (with all services, fixtures, and finishing's built in) reduces on-site complications and requirements for skilled workers. The ability to use automated fabrication and assembly machines (factory robots) creates a direct link within the digital

[55] see: Section 7.1.2

chain. The speed and ease of on-site installation also reduces cost and unpredictability of site climate, and labour conditions. The digital chain can assist with the management of all of these issues. The weak links in this digital chain however, are the issues related to quality and tolerances of on-site construction (typically the building foundation) and the risks of transportation and final on-site placement, connection to the foundation, and jointing and assembly of modules.

"Chunk assembly", is a sub-set of prefabrication, where a larger proportion of the architectural project is conceived as in-situ construction, and where large modules or components are conceived and fabricated to "plug-in" to the on-site structure.

Within digital design and fabrication, *chunk assembly* has advantages of a smaller scale and often reduced complexity of components, allowing for the potential of smaller scale machines and facilities. Additionally, increasingly the business model from aerospace and automotive is being adopted where specific components can be outsourced, manufactured, and supplied by individual specialist companies, with specific expertise in the various systems, materials, or skills and techniques, as is required.

This method has been adopted from the aerospace, train, and shipbuilding industries, as a method to mediate the advantages of speed and distribution of labour, as well as to find flexibilities and economies of suppliers and market competition. The application of this method into architecture has strong potential when the size, complexity, and repetitiveness of components is at an appropriate scale. This scale is determined by the economics of the project, its context, and also the intelligence of the designers and constructors in using the available tools.

3.5.4. Robotics

The use of robotics in architecture and construction thus far, has been (mostly) limited to the factory or industrial setting. The technical complications of robotics are such that their use is still highly dependent on the availability of referencing and positioning information, and this in turn implies that working on a (potentially chaotic and messy) construction site is still problematic. As such, robots "like" to know their context, and having a fixed context is still the most appropriate setting for their use.

Industrial robots have been employed in other industries since the 1970's but are only currently making headway into architecture. There are two fundamental reasons for this: The first is the cost and trickle down economics of robotics, in that they are only now available at a cost point where they are of value in architecture.[xliii] The second reason is the disenfranchised tradition of architectural prefabrication, its use of factory production techniques, and the resulting impression from the consumer that factory techniques do not result in products of for high quality and high architectural value.[56]

Robotics have strong potential for change in architecture. Programmable robotics, with exchangeable tools are increasingly being employed in different roles in industry. Their adaptability and programmability allows for their use in both mass production and mass customization modes. In situations of rapidly improving software controls; the flexibility of working configurations make robots more economically tenable, and less risky as a significant long-term production investment.

> *"What will the factory of the future look like? One possible answer might be: Machines are tools that are built according to the scientific theory of the day."*[57]

Although robotics are typically used for mass production, their flexibility of movement and adaptability of both tooling and programming makes this technology adaptable to efficient

[56] Cobbers, et al. (2010): p.41
[57] Flusser, V. (1999):p.46

custom or individualized "short-run" fabrication cycles. This capability is of paramount importance in architectural production.

Awareness of advancements in industry, and insight into the "trickles down" of technology, can allow the avant-garde architect to take advantage of the current robotic emergence.

3.5.4.1.1. Robotics unleashed

The advancement of robotics and their application outside of industrial settings of the factory or lab, are still the realm of specialized applicationsxliv, however architectural researchers are already re-contextualizing these developments. Recent projects include combining biomimicry behaviour (in the form of swarming algorithms) with autonomous but networked flying and brick carrying robots, used to build discreet structures from algorithmic digital designs. As well as sensor laden mobile robots which can work in heterogeneous and complex site-conditions, be aware of their context, and build autonomously according to changing conditions.

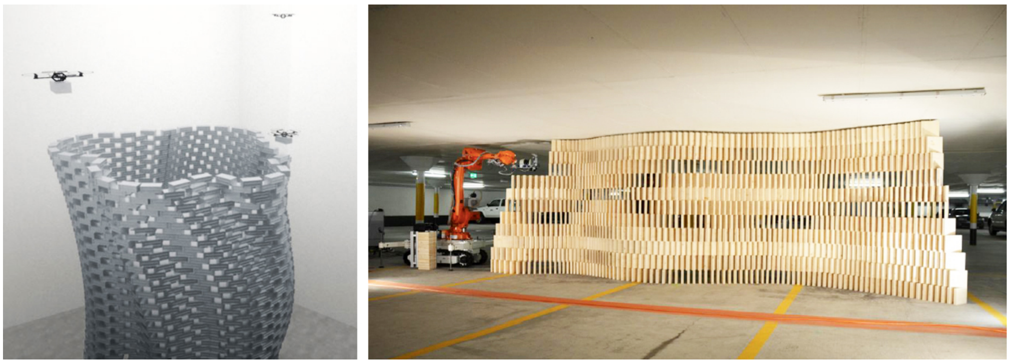


Fig.3.5.4: a). "Flight Assembled Architecture": FRAC Centre, Orléans, FR. b.) Context aware, mobile assembly robot: DFAB, ETHZ. Zuirch, CH.

3.5.4.1.2. In-situ robotics

Current research includes investigations into how robotics can be put into practice on building sites. This work, based on previous (unsuccessful) projects to automate the erection of tall structures and skyscrapers, relied on significant investment and innovation in infrastructure. This technology was efficient only when adequate scale, standardization of construction, and digital control of the process was possible. These technologies, mostly developed in Japan and Asia, were mostly abandoned in the 1990's, due to the constraints of method, but also overwhelmingly due to economic change in Japan.

"The projected lack of construction workers lost urgency when the Japanese economic bubble burst in the late 1990s. Research and development budgets shrank quickly and there was little opportunity for exporting the technology; the world was not ready for construction robots."[58]

New versions of this concept have the advantage of a decade of technological evolution. Current platforms[xlv] are iterative modernizations from the 1990's models, however they are already incorporating advanced robotics, precision laser measuring, and automated material delivery systems. As this research advances innovations in the use of machines and robotics in construction and architecture solidify resulting in new potential for the digital chain.

---

[58] Bechthold, M. (2010): p.119

3.6. Technology conclusions

Technology, and specifically digital information technology is now omnipresent in everyday life. It is interesting that as it becomes ubiquitous, it also becomes transparent. This thesis is focused on the connection between architecture and technology, but what will happen in the future if technology becomes so prevalent that there ceases to be a distinction between it and everyday life. Just as the pencil and paper before it, there may come a time when digital technology is taken for granted, and there is no significant thought invested in its role or existence in the methods of architecture.

This future is certainly not with us at the moment. The pedagogic experiences throughout the duration of this thesis are full testament to this fact!

If the practices of architecture, and specifically the methodologies used, are viewed from a critical position, then tools and processes will always be distinguishable from concepts and ideologies. However, we need to have a basis or context from which to formulate this critical position.

In presenting technology as a motivator for architectural innovation there has been a specific and very significant omission of theory. As Vitruvius claims, "architecture is the intersection of theory and practice"[59], and although each technology and application has its own conceptual basis (as has been presented), there are also overall larger concepts and philosophies at work. Three significant theories that bridge architecture and technology: Systems, Tools, and Design will be presented in the following chapter.

Endnotes:

---

[i] Extracted from: "The Information Machine" IBM film. Developed by Charles and Ray Eames.

[ii] Note: the computer is not in any way physiologically "aware", but it can be configured to accept specifically determined input and monitor all input data from context monitoring sensors in real time.

[iii] ...and extended computational systems and cloud computing.

[iv] Note: the performance criteria are still subjectively defined by a designer or programmer, and as such the criteria becomes one of the "creative" design parameters.

[v] Note: the goal may be performance oriented, ...but not need be.

[vi] Regarded as the first CAD system, SKETCHPAD was developed in 1963 by Ivan Sutherland at MIT as part of his PhD thesis.

[vii] Although these geometric forms are dimensional transformations of the 2D primitives, they are often included as primitives in 3D modelling software.

[viii]For a comprehensive overview of the development of digital design tools see: Kolarevic, B. *Architecture in the Digital Age:* introduction.

[ix] AutoLISP (AutoCAD Locator/Identifier Separation Protocol): the original programming language used in AutoCAD and other AutoDesk software programs.

[x] MEL (Maya Embedded Language): is classified as a "GUI scripting" language: the script editor records the GUI interactions in script form, providing the ability to save any set of actions as an executable macro.

[xi] Ex: VisualBasic (VB) Script, Python, and Ruby.

[xii] Example of programming languages include: Fortran, C, C++, COBOL, Java, and Processing.

---

[59] Vitruvius, circa: 30b.c.

[xiii] Hugh Whitehead, Techniques and technologies in Morphogenetic Design, Wiley Academy, 2006

[xiv] ex: CRD-Completely Randomized Design, RBD- Randomized Block Design...

[xv] Example: The Voronoi generator tool in Grasshopper, or the *Voronoi 1.1* plug-in for AutoCAD.

[xvi] When any newly generated solution consistently underperforms compared with the existing solutions.

[xvii] For greater description of EA's and GA's see: Strehlke, K. (2007). Section 3.3.

[xviii] Ex: Autodesk Revit Conceptual Energy Analysis: powerful cloud-based energy analysis.

[xix] Evaluation criteria can include any performance evaluation, which can be measured and encoded for simulation. Examples include: structural performance, energy usage, and environmental impact, but can also include occupancy factors or qualitative issues such as lighting and acoustics. A full overview is available in Kolarevic, B., Malkawi, A. (2005) "*Performative Architecture: Beyond Instrumentality*"

[xx] Ex: iPad, Augmented Reality Systems, 3D-PDF,...

[xxi] Ex: a print driver for laser cutting machines

[xxii] Ex: Slicing, contouring, meshing, or polygonalizing...

[xxiii] The first Numerically Controlled milling machine was publically demonstrated in 1952.

[xxiv] Stereo-lithography, 3D-printing, Fused Deposition Modelling, Selective Laser sintering, and so on...

[xxv] Laser, waterjet, plasma-arc, drag-knife, and reciprocal-saw cutting.

[xxvi] Such as: consumer behaviour, social networking, internet search algorithms, traffic movement, biological epidemic vectors, population dynamics, and the growth and decline of ancient civilizations.

[xxvii] Lifeclipper is an AR project at the Hochschule für Gestaltung und Kunst at the Fachhochschule Nordwestschweiz in Basel, The author of this thesis was an academic advisor for the project in its first phase in 2006.

[xxviii] Example: automotive, machine, and consumer goods manufacturing

[xxix] Quote: Senior Indian Air Force Marshal Pradeep Naik: Attribute: *"India Today"* October 8, 2010.

[xxx] Regarded as the first CAD system, SKETCHPAD was developed in 1963 by Ivan Sutherland at MIT as part of his PhD thesis.

[xxxi] This theorem is called "Manslow's hammer" and is discussed in detail in "4.3. Tool Theory"

[xxxii] "Disruptive", from the definition of *disruptive technology*: as a technical innovation that instigates a new condition or value network.

[xxxiii] For specific examples see: "Appendix: Technology in Practice: examples"

[xxxiv] Reference: client list – design2production at: www.designtoproduction.ch

[xxxv] This future potential will be discussed in greater depth in the discussions section "7.1. Exponentiation" concluding the thesis.

[xxxvi] Charles Goodyear: the addition of sulphur as a thermosetting method for plastic materials

[xxxvii] The Burj Kalif Tower in Dubai employs carbon fiber reinforcement in its foundation and floors.

[xxxviii] Electromagnetic alloy depositioning was presented by Prof. Jan Schroers, Mechanical Engineering and Materials Science, Yale University, at EPFL guest lecture: "Materials Science and Development of Complex Materials" March 29, 2012.

[xxxix] Variable Property Fabrication (VPF) is documented as a novel form of 3D-printing in the dissertation: Oxman, N. (2010)

[xl] ex: just look at the popularity and critiques of style in "Mad Men"

[xli] Note: This is discussed in detail in the concluding thesis discussions, "7.1. Exponentiation"

[xlii] Note: For most industrial scale CNC machines, tolerance is at 0.1mm or finer, so the tolerance issue is truly more related to the quality and precision of materials.

[xliii] Note: it is not the inherent cost of the equipment, but rather the cost of programation, which has limited its adoption in other industries. With the reduced cost of computers and the increased availability of easier and more comprehensive CAM systems this has now fundamentally changed.

[xliv] Ex: military, space exploration, infrastructure repair and maintenance...

[xlv] Ex: Obayashi Corporation, Automated Building Construction System (ABCS), (2006)

4. Theory

4.1. Systems Theory

"The emergence of information-processing technologies in the late 1950s is considered to have acted as a formative pressure in stimulating a coalescence of scientific models (namely principles associated with systems theory and cybernetics) and artistic production in the formulation of a systems-oriented culture."[1]

– Dr. Marcelyn Gow

4.1.1. Emergence

Distinction between a complex design as a whole: "a system", and the design as its parts: "the components", has been a significant issue in design theory for decades.[2] Much twentieth century design philosophy has focused on this issue, with particularly strong links to complexity theory and its origins in differential calculus and non-Euclidean geometry. *Systems,* and the concept of associative complexity, were first understood in the antiquity as models or metaphor that could be applied to real networks but also conceptual ones. Through the concept of *emergence* in systems, philosophy, humanities, and also design theory would be able to share a common intellectual structure with science.

Emergence, is the condition when complex systems and patterns arise out of a multiplicity of relatively simple interactions. This concept identifies the fact that a system is the interaction of components and their relationships, but that it is also more than the "sum of its parts". This distinction between a design as a functional whole, and a design as a set of combined components, underscores the idea that successful project development requires two types of knowledge. First it requires *components knowledge*: the core design concepts and the way in which they are implemented. Second it requires *architectural knowledge*[i]; the ways in which the components are integrated and linked together into a coherent whole. These two concepts are fundamental to the idea of systems and the design decisions required to manipulate them. It is therefore not coincidental that these are the same criteria that define the difference between the two forms of *innovation.*

Incremental innovation induces controlled change in either components, or a change in their relationships (per iteration). If *emergent* behaviour spontaneously occurs in *iterative cycles*, then the innovation has a high propensity of becoming extemporaneously *radical.*

4.1.2. Historical development of systems theory

A primal driver of any development or evolution (and therefore also of design), is man's desire for control over his environment. Attempts to understand, manipulate, and therefore control phenomena have defined the evolution of civilization. The primal search for "primal elements" (the most basic building blocks for all phenomena) and the desire to control them is common to most ancient cultures. Theories of the antiquity (and before), formed paradigms for ancient civilizations; but are also evidence of the initial understanding of system and the basis for logical and objective thought. As civilization developed logic and objectivity, the mythological and spiritual nature of cultures was reduced[ii].

In Babylonian philosophy, five cosmic components defined the natural world: *earth, sea, sky, fire,* and *wind; t*hese were considered the "root elements". In the Greek antiquity, Empedocles of Agrigentum (494-434 BC) refined the list to four: *fire, earth, air and water*[3] and called them "rhizōmata." Aristotle later went further to add a fifth *rhizōmata*: *aether* (ether) as that

[1] Gow, M. (2007)

[2] Marples, 1961 ; Alexander, 1964.

[3] Aristotle Met A4, 985a31-3, according to Kirk (et al.) (1994):p.316

element which is not of the terrestrial world; "*that which God used in the delineation of the universe*." Plotinus, 3rd century philosopher considered *aether* to make up all things conceptually "non-material"[4].

This ancient concept of *rhizōmata* initiates two main philosophies of interest to this thesis: The first is the concept of *analysis*. That anything – any *phenomenon* – can be dissected and investigated as root elements. Once *rhizōmata* are known, any other phenomena can be explained as differential re-synthesis of these elements. The second, more pragmatic concept is that there was a field of study called *alchemy*. Alchemy was the study of combining *rhizōmata*, and it is now recognized as a proto-science and the basis for modern chemistry.

Alchemists were motivated by the idea that there exist formulae for the control and *transmutations* of materials. The driving motivations of alchemy were the cure of evils (sickness and death) the transformation of materials (e.g. base metals into the noble metals of gold, silver, platinum…), and the ability to control energy (or magics). The myth of the *philosophers stone* and other such compositions are examples of motivations promised by control over phenomena, but their result was the emergence of objective experimentation.

During the 17th and 18th century, practical *alchemy* evolved into modern chemistry. With the emergence of the Enlightenment and the positivist movement, objective determination became the prime method of investigation. The *scientific method* led to the periodic table, the understanding of molecular and atomic chemistry, and the rejection of spirituality and "ethereal" influence on phenomena. This investigation of "elements" is important to the issue of design and production, in that it puts into context the basis for evaluating phenomena and paradigms, but more so, it shows the emergence of the concepts of actions, reactions, and interactions; and an understanding that the natural world is based on interactions of *systems*.

4.1.3. Relational systems

Methods of explaining phenomena using objective principles of mechanics, matter, and empirical causality emerged in the Enlightenment. Newton's laws of motion, first published in 1687, elucidated the idea of causality between *matter* and *energy*, and reinforced the use of objective scientific investigation in physics. The mechanistic *paradigm* of the laws assumes that the world is guided by mathematical order, and insomuch it is both predictable and controllable. If given enough information it was theorized that it would be possible to identify all of the influences of a *system*, model the relationships between components, and use this model for prediction. Through the understanding of matter and energy a new descriptive method for understanding our natural environment (paradigm and phenomena) emerged.

By the end of the 19th C. Newtonian understanding of physics, space, and time became the functional paradigm for contemporary science. The Newtonian Laws of mechanics were an irrefutable mathematical model employed for everyday use, and worked at all levels of scale for known phenomena[iii]. The methods of analysis and synthesis in this age were constrained by the limits of the observational capabilities for man. As technology developed, observation became possible at extended scales, and the paradigms of mechanistic and scientific investigation were refined.

> *"Figuratively taking machines apart to understand them was the key to machine-age thinking. Synthesis is the essence of systems-age thinking."*[5]

4.1.4. General Systems Theory

In 1937 Ludwig von Bertalanffy proposed his "General Systems Theory" (Allgemeine Systemlehre), which was originally derived from his investigations in biological systems. Von Bertalanffy's objective was to create a unified organismic theory that would deal with the complexity of non-linear systems.

---

[4] Attributed to: Fludd, R. (1659):221.

[5] Hughes (2004):7; quoting the American economist Russell Ackoff (1919)

Since the enlightenment, the scientific method had developed under two assumptions:

- Systems may be reduced to components for independent analysis
- Components could be linearly recombined to describe the totality of the system.

Von Bertalanffy proposed that both postulations were incorrect. His contradiction of *reductionism* was a conclusion derived from his observations in one discipline (biology), where the understandings were then applied onto general scientific thought.

Systems Theory states that systems are characterized by components and their interactions; in this way, systems are seen as a web or matrix, rather than a linear addition of parts. Extracting any element by simplifying or abstracting the system reduces the robustness, resolution, and understanding of the system as a whole, but does not destroy it. Only through a detailed understanding of the system and its potential for non-linearity, can the systems be understood and then manipulated.

> *"… leading design professionals speak of a new awareness, of a complexity which resists the skills and techniques of traditional expertise. … they have come to see the larger system as a "tangled web" that traditional knowledge and skill cannot untangle"*[6]

Von Bertalanffy defined system as "elements in standing relationships", which can be either uncontrolled, or controlled (cybernetic) systems.[7] Controlled systems have capability for the sensing of, and reacting to, stimuli or information in their environment. This theorem was founded in *tropism* in biology, but it has been widely applied to other complex phenomena.

> *"Linear thinking is about sequences; … systems thinking is about connections."*[8]

Systems theory builds upon the concept of *holism*, presented by Jan Smuts (1927) as a refutation of Cartesian analysis and reductionist methods. Smuts defined holism as *"The tendency in nature to form wholes that are greater than the sum of the parts through creative evolution."*[9] Although both *holism* and *systems theory* focus on the system as a unit, they do acknowledge that the whole is composed of complex and inter-related sub-systems.[iv]

There are three general approaches for evaluating subsystems:

- The *holist* approach examines the system as a complete functioning unit.
- A *reductionist* approach examines subsystems within the overall system, and codifies subsystem relationships.
- The *functionalist* approach looks upward from the subsystems to examine the roles they plays in the larger system and beyond to its greater context.

All three approaches recognize the existence of subsystems operating within a larger complex and inter-related environment.

Through the exploration of mechanistic laws of energy conservation (from Newton), and biological laws of mass and energy conversion; Bertalanffy in his *General Systems Theory* proposed that all systems can be understood as organizations of sub-systems, but that the behaviour of these sub-systems is then defined through their relationships and conversion of between matter and energy.

> *"The general conservation principles of science appear to be the same whether they are applied to inanimate things, to organisms, or to psychological or social processes."*[10]

4.1.4.1. Biological analogue

The explicit starting point of *General System Theory* was the demonstration that biological and organic phenomena occurring at the microscopic level could be considered as an

---

[6] Schoen, D. (1982):14

[7] Bánáthy, B.H. (1997): 22

[8] Brown, T. (2009):6

[9] Smuts, J. (1927): 88

[10] Bertalanffy, L.v. (1948):117

abstract model for systems at the larger scales, and that *emergent* phenomenon such as complexity, feedback and self-organization were common to all scales and systems.

The application of *systems theory* to other fields shows its use as an internally consistent framework for the study, classification, and evaluation of patterns. It is a scholarly method for providing a universal and cross-disciplinary approach to evaluating knowledge structures. When applied to design, *systems theory* provides a nomenclature and set of tools for understanding complexity. This understanding is the foundation for *"systems thinking"*, conceptually viewing phenomena as a network of components and relations. This alternate way of viewing design provides a new set of abstract and conceptual tools for investigative synthesis and design.

This analogy of biological systems was taken up by other researchers and applied bi-directionally. Theories of information systems, self-replicating systems, and cellular automata, all put forward by Dr. John Von Neumann,[v] relied on the biological analogy, and were established concurrently with the development of fast reliable logic machines. The operating concepts of the first practical general purpose symbol manipulating machines, the forerunners to the general purpose computer, were made possible due to theories derived from *cellular automaton* theories.

4.1.4.2. Equilibrium

The scope of *systems theory* presumes that problems cannot be solved by a single technical solution, but must be attacked on a multileveled, interdisciplinary basis.

In algebra, any algorithm with more than one variable is not solvable unless additional knowledge about relations between variables is known. By excluding variables (the process of abstraction), it is often possible to reduce a situation and set of equations to a point such that the whole can be solved.

Systems operating in the "real" world are open systems; there is an unhindered free flow of *matter* and *energy* to and from system and its environment. To empirically "solve" a system it needs to be isolated from uncontrolled variables, such that the variables and their relationships can be derived. This is the process of abstracting a system such that it can be considered to be "closed".

4.1.4.3. Closed systems

Closed systems are constructs; abstracted and simplified versions of reality built to allow for a determinate outcome: *equilibrium*. By creating finite systems, there exists the analytical possibility of solving a multi-parametric equation which represents the system. This method is the basis of the analytical theories in biology, tropism, thermodynamics, and entropy (amongst others). Theoretically in closed systems once equilibrium is achieved the stable distribution of energy represents an ideal solution: an optimal design.

"In the 1960's, thermodynamics was revolutionized by Ilya Prigogine by showing that classical results of equilibrium are only valid for finite systems. If one allows for flow of energy both in and out of the overall system, then there is no equilibrium. In this case, due to the complexity of variables, the potential for "versions" creates an unsolvable parametric condition."[11]

In open systems external influences continually introduce new parameters or motivators. The most notable motivations are *paradigm-shifts*, from which the system completely reorients itself and must then resume an iterative evolution towards equilibrium. Design, and especially architecture and urban design operate in the context of open systems.

Methods of abstraction (ex: simplification, analytics, tabular rasa,...) are used to reduce the complexity of systems in design, such that "simple" solutions can be proposed for complex problems. In this manner, the solution is at first based on an objective *analysis* of a closed system, followed by subjective *synthesis* of placing the design back into its open system.

---

[11] DeLanda M.(1997):14

"Both classical thermodynamics and Darwinism admitted only one possible historical outcome, the reaching of thermal equilibrium or of the fittest design. In both cases, once this point was reached, the historical process ceased to count. In a sense, optimal design or optimal distribution of energy represented an end of history for these theories. However in both of these examples the theories have been abstracted and simplified for closed systems; systems which may reach an equilibrium."[12]

4.1.4.4. Feedback

When all forces in a system are in balance, no change is occurring, and the system achieves a state of static equilibrium. Kuhn states "all systems tend toward equilibrium, and that a prerequisite for the continuance of a system is its ability to maintain a steady state or steadily oscillating state. Equilibrium in a system can be achieved either through negative or positive feedback of a system in an iterative state."[13] In design, different methods are used to "push" the design in one direction or another. These methods of "working" the design, imparting a force and direction, are analogous to stimuli feedback for a responsive system.

The continuance of a system and its motivation towards an optimal state through the use of "feedback" is fundamental to the evolution of *general systems theory*, but the same concept is also used in contemporary design and digital systems to find optimizations.

4.1.5. Cybernetics

Despite the contemporary association of "high tech" with the term *cybernetics*, it is actually a term from the antiquity, to describe the process of "self correction"; the responding of action to changing conditions and stimuli: a feedback system. The root of the word *cybernetics* comes from the Greek word "Kybernetes" which means pilot, or steersman (from the guiding of a ship). This ancient ideological concept[vi] was used in intellectual discourse, and is described as the process of moving back and forth between *logic* and *rhetoric*.

The modern interpretation of *cybernetics* is the study of conceptual regulatory systems. The re-introduction of the concept is traced to 1834 when it was used by French physicist André-Marie Ampère.[14] His definition of feedback systems was rooted in understanding electrical signals, and specifically how they could be combined to create interference or amplification effects.[vii] It was Ampère who proposed that through use of electromagnetism, electronic signals could encode information[15] and eventually could be used in the control and flow of information signals. The development and popularization of *systems theory* brought this issue of *information control* and its use in *feedback* systems into focus for contemporary technology.

Contemporary *cybernetics* evolved through the development of goal-seeking control systems in autonomous and semi-autonomous machines during the Second World War. The American mathematician Norbert Wiener, adopted and developed the concept through automatic aiming and firing of anti-aircraft guns. His investigations of *information theory*: the investigation of signal processing, storing, and communicating of data, gave him new tools for understanding complexity in dynamic systems. Wiener's ideas resulted in the 1948 publication of "Cybernetics or Control and Communication in the Animal and the Machine".[16]

Weiner's subsequent development of electronic signal as a feedback mechanism, is the basis of contemporary digital *cybernetics*, and is used for problem solving in both stochastic and deterministic optimization algorithms.

---

[12] DeLanda M.(1997):14

[13] Kuhn, T.S. (1974)

[14] Ampère, A.M. (1834)

[15] Ampère, A.M. (1822)

[16] Wiener, N. (1948)

4.1.5.1. Orders of Cybernetics

The level of interaction that the system has with its surroundings is called its *order*.

First order cybernetics systems are systems that respond to external input, either a direct input applied onto the system from an operator, or *stimuli* coming from the environment. The system has the ability to "correct" itself due to the information being presented, and these corrections show a small degree of self-manipulation. Larger manipulation comes due to the repetitive and cyclical nature of such systems; with each iteration there is correction, and the system is self-controlling when it is looping cyclically.

Feedback can however be used at a higher level of transformation. Cybernetic theory recognises that a system can adapt to stimuli by changing its *environment* rather than changing *itself*. *Second order cybernetics* recognizes the inclusion of an observer (or the environment and their behaviour, as a second higher *order* of interaction.

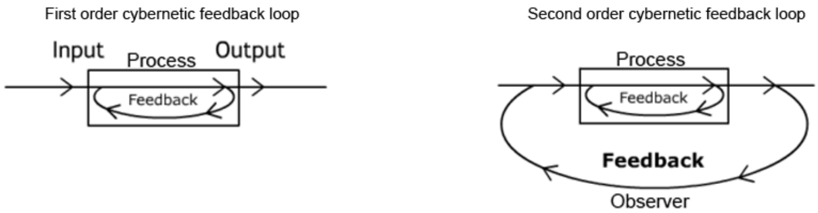


Fig. 4.1.5.1. Cybernetic feedback loops: a.) First order cybernetics; b.) Second order cybernetics.

Second order cybernetics, also called "the cybernetics of cybernetics" is the concept of an *autonomous control-feedback loop,* or a "circular causal relationship". Conceptually, an observer to the system can also be the cause of change and be affected by change, as with Schrodinger's Cat[viii], when the investigators observe a system, they affect it, and, are affected by it." When issues of autonomy, self-organization, and how the observer influences the system are combined then the system is operating at the level of *Second Order Cybernetics*.

4.1.5.2. Second order cybernetics in design

If one applies the second order cybernetics to the *process of design;* studying the field of design (not the act), the result reveals how *design* (again, as a discipline) evolves. A step-by-step example of this explains the concept:

1. A designer creates an interesting and novel design solution, which is both responsive to its brief, but is conceptually innovative in terms of ideas, forms, and technology. This project is interesting enough to be published.
2. This novelty then attracts the attention of other designers.
3. The novel design provides new knowledge and influences the designers and their own methods and designs.
4. Resultantly, the epistemology of the larger group of designers evolves.
5. The new theories, methods, knowledge and results from them are put into practice in the next generation of design solutions.
6. These in turn, affect the next generation of designers and their designs.

This is a "meta-level" *positive feedback loop*, and is analogous to *second order cybernetics*.

"Contemporary design techniques are part of a complex feed-back loop, and they produce new effects which act on or influence behaviour and technical performance."[17]

First order cybernetics are artificial by nature, as they are closed systems of stimuli and response. *Second order cybernetics* underline the relationship between system and environment, and remind us that isolated or closed systems do not occur in nature, and as such most *higher order systems* are complex in nature.

---

[17] Rahim, A. (2002):p.5

4.1.5.3. Higher order systems

Third order cybernetics can be defined as being an overview of the interactions between second order system and a higher order "manipulator". A single order function gives a single answer (a point), a second order function results in a range of answers (a line); a third order cybernetic *function* is based on a "triple loop", and as such *dimensionally* the function when calculated will result in multiple realities (a field of possible versions). As such the solution of the system emerges not as a singular solution, but as a two-dimensional field of possible solutions within the parametric variability of the problem.

It has been proposed that the third loop is the "choice" of the observer, and the subjective intervention of an observer (or designer) is the only manner to produce a solution. Third order cybernetic systems are parametric systems, with a range of possible solution, this theory is called *Versioning.*[18]

When modelling design with increasing layers of self-referential variables, the *order* of the model is increasing. With each order of variability the complexity of the system increases exponentially. The ability to solve higher orders problems quickly exceeds the scale of human problem solving. This is the advantage of using digital computation, as it allows scientists and programmer to approach high complexity problems (such as advanced environmental modelling) with greater accuracy and probability.

4.1.6. Application of Cybernetics

In digital computing, *cybernetics* and feedback loops are fundamental logical methods used for control programming. The success of *cybernetic theory* in the 1950's led to its application in other emerging fields of the time including cognitive sciences, neuropsychology, conceptual mathematics, and biophysics.

Architects in the early 1960's, notably Gordon Pask, Nicholas Negroponte, and Cedric Price were highly influenced by these theories, and applied these concepts to architecture. Resulting projects from the *Architecture Machine Group*[ix], and proposals from Price such as *Fun Palace* or *Potteries Thinkbelt* are early conceptual depictions of cybernetics in architectural form.

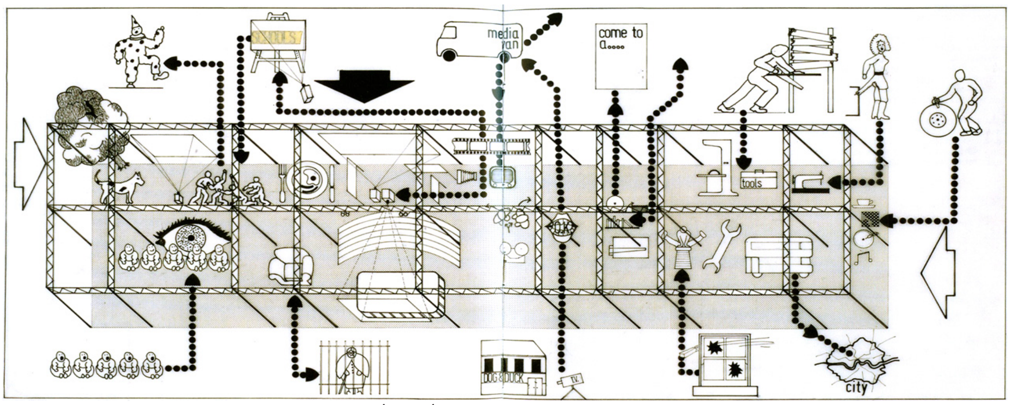


Fig. 4.1.6. Fun Palace; Cedric Price (1961): Cedric Price's proposal for an architecture that integrates the new "machine future" and allows the newly liberated worker a place for life's enjoyment.

"Automation is coming. More and more, machines do our work for us. There is going to be yet more time left over, yet more human energy unconsumed. The problem which faces us is far more than that of the 'increased leisure' to which our politicians and educators so innocently refer. This is to underestimate the future. The fact is that as machines take over more of the drudgery; work and leisure are increasingly irrelevant concepts. The distinction between them breaks down. We need, and we have a right, to enjoy the totality of our lives. We must start discovering now how to do so."[19]

---

[18] Sharples, et al. (2003):p.6.

[19] Obrist, R. (2003): Re: CP. *The Architecture of Cedric Price*

The early concepts of cybernetics, computers, and technology were that they would be as much a social force as a labour force. The concept of automated and sensor laden environments have not (yet) materialized. Since this time, other “systems reactive” architectural projects[x] have engaged the concepts of cybernetics. With the inclusion of digital technologies in the form of sensors, actuators, and control systems these projects are now relatively commonplace. The fantastical architecture of this time has conceptual connection to the contemporary developments, but technology has lost the “fun”.

Cybernetics, when practically applied have made possible fields of: mechanical automation, maschinic computer control, and robotics, and second order cybernetics is the basis for research in artificial intelligence and adaptive digital learning systems. As Weiner originally noted; the mechanistic and electronic metaphor of signal processing extends to the understanding of the structure of the brain.

> *“Thus, there is a certain analogy between a nerve fibre and a flip-flop circuit, an electric circuit with two, and only two, states of equilibrium. …The nerve fibres communicate with one another by junction points or junction systems known as synapses, and in these the question whether a new message is established in an outgoing fibre depends on the precise set of incoming messages received from various fibres. … In view of this, I was compelled to regard the nervous system in much the same light as a computing machine.”*[20]

4.1.6.1. Digital Cybernetics

No human being has had a complete mastery of all human knowledge in recent time.[xi] A thorough mastery of all knowledge would be problematic for even the most intelligent human brain. Given the computers unique systematic capabilities it would be possible for a computer to have such knowledge in memory, and the resulting system would be functional. Combining this “knowledge” with the attributes of speed, tireless operation, unfailing memory, and fast connected communication, and the result will be formidable. This is still a cybernetic vision for the future, but given current knowledge systems, it is a clear possibility.

Systems can be identified by their structure: a *real system* is any system composed of matter and energy; an *abstract or analytical system* is a pattern system whose elements consist of signs and/or concepts (ex: language, mathematics, logic). Unlike *real system*s, which can only exchange information, abstract systems –*are*- the embodiment of information.

Complex design representations (for example parametric models) begin their existence as *analytical systems.* As the information of the system is processed based on the algorithms that define the model, the result become increasingly explicit and representational. The systems eventually metamorphoses to become a *real system* as embodied the production phase.

```
#!/bin/bash -e

# create a new executable
cat $0 > temp
mv temp $0
chmod +x $0

# schedule that executable to run in the future
echo "sh $0" | batch
```

Fig 4.1.6.1. Autopoiesis code in BASH script

An *abstract system* can also be used for the higher order process of *autopoiesis* ("self-creating", or self reproducing). Consider a programmed algorithm, which has the ability to create text output. Programming can be done such that the output from an algorithm is a block of text, which can be interpreted again as another algorithm.

Such self-reproducing programming can also be programmed to be cybernetic and responsive to its environment. As an algorithm produces an adapted second algorithm, the programming can be seen as a rudimentary evolving system. If the algorithm is able to change the environment, and specifically the key environmental stimuli of the algorithm, then the program alters the equation for the creation of the next iteration. The system is then operating at the second order, and has achieved an evolutionary feedback loop. The *rhizomata* of Darwinian biological evolution encoded as an abstract algorithmic functions.

[20] Wiener, N. (1964). p. 268

4.1.7. Matter, Energy, and Information

General Systems Theory and Cybernetics are both concerned with determining what the components and relations were within systems such that they could be understood. In natural science the two primal elemental components are *matter* and *energy*, these abstract quantifications can be used to describe the state and relationship of all natural bodies. The additional element of *information*, which defines both embodied organization and signal between components. These thee conceptual *rhizomata* have been proposed as a system to conceptually describe all existing phenomena.

> *"In 1901, half a century before Wiener's introduction of information as a third category of description, the historian Conrad Matschoss described the condition for useful work as being expressed by a uniform combination of three factors: power, tools and intelligence."*[21]

First André-Marie Ampère, and then Norbert Wiener demonstrated that signal is the embodiment of information. The ability of a system to interpret a signal and to react to it is the basis for relational complexity[22].

> *"A system is; to quote the biologist von Bertalanffy, a complex of components in interaction, comprised of material, energy, and information in various degrees of organization."*[23]

Any biological, mechanical, or (now) digital phenomena that can "handle" information, also reacts to that information in some way. From this observation it has been concluded that information must be distinct from both matter and energy within a system[24]. This concept of independence of information is at the core of the cybernetic model. Systems require matter and energy for existence, and they require information for self-governance.

In his 2009 Doctoral dissertation[25], Dr Christoph Schindler develops the argument for *Matter, Energy, and Information* further. His use of the categorization is specifically applied to "production phenomena", and he presents his case that the parameters should be considered as the *rhizomata* for any contemporary production process or methodology.

> *"General system theory, as applied today in interdisciplinary discourse, is a comparatively recent development. Ludwig von Bertalanffy (1948) introduced the idea of systems as opposed to the isolated examination of singular phenomenon. In his creation of 'cybernetics' Norbert Wiener (1949) proposed information as a third parameter in addition to energy and matter, stating 'Information is information, nor matter or energy."*[26]

Schindler's statements are supported with reference to academics in the fields of history and theory of industrialization, such as historian Dr Martin Füssel, who writes*, "there is consensus that three categories: Material, Energy, and Information hold great importance for the analysis and synthesis of technical systems".*[27] Although the acceptance of these three parameters comes from philosophy and history, Schindler argues that the theories, when applied to the phenomena of architectural production, hold equally true.

4.1.7.1. The new rhizomata

The conceptual *rhizomata* of all phenomena and systems are: *matter, energy,* and *information*.

4.1.7.1.1. Matter

Matter is defined as both the atomic understanding of matter: "anything that occupies a physical space"[xii], but it is also understood as *material*: matter which has a set of specific

[21] From: Schindler, C. (2009):34. Translation by author

[22] Ropohl (1986):66

[23] Burnham, J. (1968)

[24] "Information is information, not matter or energy": Wiener (1948):155

[25] Schindler, C. (2009)

[26] Schindler, C. (2009):34-39.

[27] Füssel, M. (1978):13 (translation by author)

properties (such as weight, colour, condition,..). For the purposes of this thesis, matter is raw material for production, and material is processed substance with inherent qualities.

4.1.7.1.2. Energy

Energy is understood in its classic Newtonian definition: "the ability to do work", but also in its various transformed or converted phases of power (thermal heat), electrical power, chemical potential, optical or acoustic wave energy and nuclear energy. For the purposes of this thesis; energy is the application of work, (example building = manpower), it is power to operate machines and processes (electricity), but it is also the measure of embodied energy: the amount of energy required to process matter from its raw state into a refined design state.

4.1.7.1.3. Information

Information is the most ethereal of the three parameters. It should be conceptually understood both as signal (the impetus of instruction, or at its basic the position of a "switch"), as well as organization or pattern potential (ex: the organization of atoms to create a specific molecule). For this thesis information is the control of the manipulation of energy and/or matter, such that a specific result is achieved. A signal is used to make information explicit, however this does not mean that all information is inherently technological.

4.1.7.2. Combinatory change of state

Just as with the *rhizomata* of alchemy, the theorists of *matter, energy, and information* understood that the conceptual aggregation of these *rhizomata* would result in complex synthesis and changes of state.

Energy and matter are combined to changes the state of a material, such as to make it "workable"; information (or design knowledge) is added to form the workable material into a shape. The process transforms disorganized (raw) matter into higher *order* organized matter.

Example: A brick is made of matter, formed and fused by energy. The information that resides in the brick is the material properties and dimensions. The information that the mason adds to the system is the position and orientation of that brick in space. Altering patterns of assembly from standard bond adds complexity (more embodied information). If more complicated building blocks are fabricated that are bigger, or that have odd shapes, or that work as a system (ex: lego) then the embodied matter, energy, *and information* all increase. If these new blocks allow for greater ease and speed of construction, it is because i*nformation* has been used to mediate the on-site energy. A given problem within a context can be resolved by mediating matter, energy, information, or any combination there within. In this case complexity is shifted from the level of overall assembly, into the component, with the result of saved time on site.[xiii]

In a production system, energy and information are used as transformative potentials. The application *rhizomata* to one another results in change of state, and the matter itself is reconfigured into higher order of complexity. This conceptual process can be used to define and explain technological evolutions, and when the results are productively significant, the change that such technology brings to workflow may cause industrial revolution.

> *"The industrial technological revolution is none other than the transition of socio-technical systems of the hand-tool technology to the system of machine-tool technology"*[28]

4.1.8. Future Systems

Systems thinking is now the dominant epistemological manner for conceiving of world-views. It is a valid problem solving approach in disciplines that deals with complexity; as such, its value to conceptual design has become far more obvious with digital design and parametric programming. Such approaches to design acknowledge that small catalytic events can cause

[28] Paulinyi, A. (1990): 306 (translation: author)

large changes and chain reactions in complex systems, and digital programming can manage such complex interactions. Likewise, *systems thinking* focuses on cyclical rather than linear causality (as do logical operands) and is used in the analysis and development in many types of system: natural ecosystems, scientific, engineered, and conceptual.

This approach to design, and the propensity to *adopt and adapt* has provided design with a number of metaphoric analogies: *the building as machine* of Corbusian modernism, the *building (or city) as circuit* proposed by Pask and Negroponte, and reinforced by Eisenman, and now the current metaphor is *architecture as organism*.

Specific and different emphasis on the proportions of *matter, energy,* and *information* define each of these three design metaphors, and with their progression the (perceived) complexity of the system increases, and the resulting demands on both design and production intensify. The primitive geometric forms and linkages of mechanistic style are (by purpose) less complex to make. The forms of the electronics era are more complex but take advantage of repetition and mass production knowledge. The current organic aesthetic has been made possible by the capabilities of both digital design and digital fabrication that manage the complexity of free-form production.

> *"… All buildings are embodiments of a mesh of interlinked concepts or interlinked topics. These concepts cannot successfully exist in isolation, and describe physically interdependent systems. To this extent, a building in gestation is an autogenetic entity fulfilling many of the criteria of a living system."*[29]

The biological analogy is however also changing the traditional perception of architecture as a static construct. In the digital medium, the possibility to strategize using time-based aspects of performance and behaviour alters the fundamental concept of design from being static to dynamic. Organisms perform; they adapt, react, are composed of many symbiotic systems, and they have feedback relations with their environments. The concept that a building "behaves" is not new, but the ability to model and simulate it, in first and second order cybernetics, creates a new dimension of design. The current avant-garde concepts of "organic" architecture have little to do with complex free-form shapes, but rather are heavily invested in *systems thinking*, performative *tropic* behaviour, and the balancing of *rhizomata*.

Design thinking combined with digital tools allows for a dramatic increase in computational and representative complexity. The fact that digital systems are making possible the design metaphors of organic life and biology should in no way be seen as an irony; but rather it should be understood as a digitally biased return to the instigative concepts of Ludwig von Bertalanffy that our contemporary understanding of the world is rooted in the investigations of natural systems. The *systems thinking* approach modulates the design processes of architecture, and digital technologies are the tools for fine-tuning the result.

4.2. Tool Theory

> *"We become what we behold. We shape our tools and thereafter our tools shape us."*[30]
>
> – Marshall McLuhan

To understand impact of change due to technology on a profession, it is essential to understand their role and impact of tools on the philosophy of design and the conceptual approach of designers.

Tools originate as a reaction to a specific problem; the innovative "by-product" of inquisition. Tool development is a form of creativity unto itself, and, as with design, if the resulting

[29] Gage, S.A. (2006) The wonder of trivial machines. Pg. 777.

[30] McLuhan, M. (1964):p.36, paraphrased from: Alexander Pope and William Blake

product is successful it is evidence of an implicit understanding of the problem by the designer. In evaluating a tool, there is insight to the designer and their approach, as well as the context and problem that they have solved. Tools are used to facilitate a task, to enable investigation, or to enhance an otherwise underpowered capability; and should therefore be understood in an abstract definition; as (actual or conceptual) constructs, used in resolving physical, or intellectual problems.

4.2.1. Categories of tools

Tools, at their fundamental level, can be conceived as appendages, extensions to the user that enhance their capabilities. The traditional interpretation of a "tool" is that it augments the physical abilities of their user. This is clearly understood when perceiving of a hammer as a hard and massed extension of the hand, which enables the user to drive a nail. However other types of tools can be classified based on how they augment their user:

- *Tools to extend physical capabilities*: this grouping includes most "working" tools, but should also be conceptually extended to constructs that enhance any physical capability. (ex: a bicycle: a tool for speed, the pulley: tool for lifting power, or the ladder: tool to extend vertical reach.
- *Tools to enhance senses:* Tools such as the telescope, microscope, microphones, and X-ray machines, all extend human senses and give us insight into phenomena that would otherwise have been imperceptible. Many such tools are responsible for modern science, and advances in technology.
- *Tools for manipulating nature:* These are constructs that interact directly with natural systems and modify them such that they are useful. The most obvious technologies are associated with agriculture, water systems, and chemistry, but on-going developments in science extend these tools into biology, genetics, and also the material sciences.
- *Tools to enhance intellect:* This final category includes constructs that extend our mental abilities allow us to find, analyse, and classify information, and to formulate and articulate concepts and knowledge. Tools in this category may be fundamentally conceptual and systematic (for example mathematics or language), but there are also physical manifestations of these tools, which allow for comprehension, and more specifically manipulation of the conceptual system (for example the abacus, the typewriter, …and now the *information machine*: the computer).

Tools employed in design and architecture may be allotted into all four of these categories. Physical tools include drawing, drafting, and modelling aids, handcrafting tools, as well as all tools and machines associated with fabrication and construction. Tools to enhance the senses include all measurement and surveying tools. Tools to manipulate nature include synthetic material science, hydrology, and other forms of environmental engineering. Intellectual tools include language, regulations, heuristics, databases, and all forms of information processing.

4.2.2. Adaption

> *"If experience shows us anything, then it is that technologies are not merely aids for human activity, but also powerful forces acting to reshape that activity and its meaning."*[31]

The successful use of tools requires the development of skill. Initially a tool is perceived as an appendage; there is a disconnect between the user and the tool such user must adapt themselves to the way that the tool functions. Through practice and repetition dexterity with the tool is achieved, and with this dexterity come an adaption of the parasympathetic nerves and coordinated reflexes. The user slowly adapts to the requirements of the tool.

An acknowledgement of this adaptation time is clearly present in the methods of teaching design. Initially teaching focus on the development of "output skills" working the media that are used to communicate design ideas (both evidence of quality of control of the medium). The development of concept and design work, and the ability to assess and critique them are

---

[31] Winner, L. (2004):p.105

dependent on the ability to communicate the work effectively. The tools employed for this do not always neatly fit into any one of the tool categories (as stated above), but rather the tools are often complex in that they help accomplish both physical and intellectual tasks. When used properly the tools should encourage the user to reflect upon their use at hand, on the chosen methodology, and on the design content being proposed.

This notion of "mirroring tools" is proposed by Richard Sennett as a part of the "intellectual tools" category. Sennett proposes that *"a mirror tool …is an implement that invites us to think about ourselves"*[32], but I extend this definition to include tools that invite us to reflect also on the work and methodologies that we are engaged in. Tools, inherently, invite us to distil the task at hand into discrete steps. They are a catalyst for abstraction and subdivision of complex problems, and in turn they help focus the approach to iterative problem solving. The constraints of a tool may reduce the possibilities for originality in the individual steps, but they therefore highlight the opportunities for creativity in combining the steps: Tools are a vital component in the overall synthesis of a solution.[33]

As a practitioners experience with the tools improves, the working intentions and their ability to communicate also improve. Once a practitioner has "mastered" the first sets of tool skills, then the critique and teaching opportunities can shift focus away from skill-building, and onto intellectual issues of concept, formulation, and development.

4.2.3. Tools in design

Excellence of design relies two skills of the designer; on their ability to respond to the design problem, and on the skilled use of their tools. Wide assortments of tools and aids are employed in all phases of design and production, with the main task of refining the speculative into the realizable.

Specific design tools are used to amplify and test the methods of creativity and synthesis, and then other tools are used to elucidate and develop the design into information, which can be effectively passed into production. In fabrication or construction, other tools still, are used to make components, ensure accuracy of installation, test quality, and certify compliance with the given specifications and regulations.

There is a reciprocal relationship between design production and tools. It is obvious that the process of design is strongly dependent on tools for the development of the creative process and also the efficient output and communication of the design, but inversely there is also a profound affect that tools can have on a project; tools are not benign within a process.

As technologies become extensions of the user they becomes both empowered, but also constrained. All tools have inherent limitations and constraints, and the potential for work is constrained to what the tool can do effectively. These limitations however, exert both a working influence and also a fundamental psychological influence on the user, known as the "law of the instrument", or as Maslow's hammer.[34]

4.2.4. Maslow's hammer

> *"It is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail."*[35]

Maslow's hammer, depicts the over-reliance on a single tool and the temptation to formulate all problems from the context of the tools at hand. This form of instrumentalism[xiv] includes the French theory of *déformation professionnelle*[xv], the theory of looking at things from the constrained point of view of one's profession. The psychological result of this condition is that users are more likely to try to find a way to work with a tool or method that they already know rather than to learn a new one; even if the new method would be more optimal or provide a better result.

---

[32] Developed from: Sennett, R. (2008):84

[33] Sennett, R. (2008):82

[34] Maslow,A., (1966):12

[35] Maslow,A., (1966):15

Although this concept is seen as restricting optimization, it does have advantage in that it provides for innovation from within the context of the tool. This is the basis of the "work-around"; the use (or misuse) of tools for purposes other than what they were conceived for – the creative use of tools for alternate practices.

The "*work-around*" is an important developmental step, as it promotes innovation on a specific tool, and it reinforces the concept of diversification and looking at a system from "outside the paradigm" of original intent. When a practitioner uses a tool with greater frequency there is a natural motivation to restrict working methods and expectations to the tool of choice. This explains why, after working with a particular tool over time we lose our aptitude for working with alternative tools, which can still accomplish the same task. Through the misuse of tools the user acknowledges the limitations, and must reflect on whether the tool is truly usable, or if the entire methodology should be altered.

Misuse of tools, however, has a danger of bi-directionality:

> *"Skill is a trained practice; modern technology is abused when it deprives it users precisely of that repetitive concrete, hands-on training. When the head and hand are separated, the result is a mental impairment – an outcome particularly evident when a technology like CAD is used to efface the learning that occurs through drawing by hand."*[36]

Here, Sennett argues in the context of Maslow's Hammer, that tools have a propensity, not only to extend the capability of a worker, but also to facilitate the laziness of a worker. If a tool (a computer) is primarily an intellectual tool, then it has potential to reduce effective learning, thinking, and understanding of a problem. Although the efficiency of a method may improve, the overall method may stagnate over time.

4.2.5. Selection of tools

The adoption of tools is heavily influenced by economic, efficiency, and demographic considerations, but it is not an overstatement to say that technological progress has its own momentum. Changes within technology are not always consistent with the intentions or wishes of the toolmakers, nor those of the tool users. External pressures such as economic competition and the drive for further productivity can accelerate the need for adoption of tools, even if the skill and knowledge of how to use them is not present in the workforce. Sometimes our tools do what we tell them to do, other times we adapt ourselves to our tools requirements.

The expertise of a professional is partially demonstrated in their skilled use of tools, but it is also manifest in their ability to choose the most appropriate tools for a specific task. A designer who is able to modify or create their own tools; tools that are refined to function in a very specific and optimized manner, will improve their artistry and effectiveness of design. If the use of tools extends our capabilities, then the ability to adapt tools extends our ability to specialize and optimize our capabilities, and adds a level of innovative flexibility to the cycle.

4.2.6. Plasticity and tools

The regular use of tools changes the manner in which we approach a problem; within this fact there are two specific issues to consider. The first is the physical issues associated with the use of the tool; its capabilities, advantages, but also its constraints. The second issue to consider is the effect it has on the psychology of the user, and specifically how the tool empowers or affects the intellectual approach of the tool user.

Recent scientific discoveries have shown that the brain is similar to other biological systems in that, under regular stresses, the brain is able to "re-wire" itself, and to adapt over time to particular tasks and stimuli. This adaption is called neuroplasticity, and experiments have shown that subjects who regularly solve problems of a similar type are able to adapt to solve the problems more efficiently over time.

---

[36] Sennet, R. (2008):p.52

This same neuroplasticity allows the brain and the musculature, reflexes, and coordination to adapt to using tools. The brain has the ability to adapt and reprogram itself "on the fly", altering the way it functions as a response to the pressures of intellectual and physical context. When a skilled user picks up a tool, his brain perceives that tool as an extension of the body[37]. This ability, in combination with other cognitive skills is what makes experienced users good at using tools, and as the experience grows it also makes them adaptive to new technologies, especially tools that have similarity to what they already know. The ability to abstract and envision a tools' working method and then apply the abstraction creatively to a similar problem is a the basis of iterative innovation, and a fundamental stage of radical innovation.[38]

> *"One of the most important lessons we've learned from the study of neuroplasticity is that the mental capacities, the very neural circuits, we develop for one purpose can be put to other uses as well."*[39]

Tools make a distinct impression not only on how we execute the solution for a problem, but also on the way that we approach the problem. Going back to *Maslow's Hammer*; if we are given a specific tool, over time the way that we think about problems will change.

But what happens if the tool that we are given is a tool that has been constructed for ultimate intellectual and procedural flexibility?

4.2.6.1. Plasticity and the digital medium

The computer is called the "universal tool". Much like the brain, a computer is a tool whose primary purpose is to "process" information. Unlike traditional machines, the computer relies on programming for its every function, and that programming is highly adaptable. The brain has a complex (and not altogether understood) method for processing information, but within this processing it relies on personal experience, learned behaviour, and other intellectual constructs (such as language, mathematics, ethics, and logic) to resolve (or at least think about) problems. The computer by contrast has only one working medium, in that at its root operational level, it is strictly confined to processing rules of logic. However the similarity in both systems is that the (conceptual and intellectual) tools used are layered, complex, and in many senses *plastic*.

> *"The mechanical conception of the brain both reflected and refuted the famous theory of dualism that Réné Descartes had laid out in his Meditations*[40] *of 1641. Descartes claimed that the brain and the mind existed in two separate spheres: one material and one ethereal. The physical brain, like the rest of the body was purely a mechanical instrument that, like a clock or pump, acted according to the movements of its component parts. But the workings of the brain, argued Descartes, did not explain the workings of the conscious mind. As the essence of the self, the mind existed outside of space, beyond the laws of matter."*[41]

With the progression of science into the enlightenment, Descarte's concept of dualism was abandoned, however, one thing that was kept was the metaphor of the brain as a "thinking machine." The invention of the computer was later instigated by this metaphor, and the metaphor has been subsequently reinforced by the creation of the machine. Both scientists and biologists have now adopted this metaphor, and the most advanced current research refers to the brain as a combination of "circuits", and as having "hardwired" behaviour traits.[xvi]

The computer, like the brain employs layers of tools to process information. At the core there is a base of reasoning: in the computer this is best described as the hardwired ability to process very simple mathematical operations (binary operations happening at the level

---

[37] From: Balter, M. (2008)

[38] Balter, M. (2008)

[39] Carr, N. (2010):75

[40] From: Clarke, D.M. (ed.) (2012)

[41] Clarke, D.M. (ed.) (2012):p.22

of the transistor)[xvii], and this in turn provides the basis for logical operations. The relation between simple math and logic is programmed as a core set of rules of the processor. This basis however then provides a platform for much more complex tools to be constructed. This is the essence of the universal tool, or otherwise exemplified as the plasticity of the digital medium.

"The existence of machines with this plasticity has the important consequence that mean (considerations of speed neglected here), it is unnecessary to design various new machines to do various computational purposes. They can all be done with a single digital computer matched with suitable programming code and input."[42]

As digital technology has evolved the limitation of speed (that Turing noted) has become less of a restriction. Processing "FLOPS" (floating point operations per second) are the measure of computational power; and advances in processing technologies have consistently followed Moore's Law[xviii], such that we are now measuring the fastest supercomputers in *PetaFLOPS* (10^{15} FLOPS). Computational design tasks that were once unimaginable are now routine, inexpensive, and the technology on which to execute them is (in the developed world) pervasive. As technology and computing power advances the comparison between the brain and the machine get closer, and the effects of interrelatedness of plasticity between the two is increasingly blurred.

4.2.7. Digital Tools in Design

Although individual designers make decisions about form, relations, geometry, and content; the final product representation is still based on the ability to execute the design into physical form. The skilled methods of use, and the constraints of a tool have a significant influence on the resulting product.

The pervasiveness of the computer, and the inherent plasticity or "re-programmability" of the digital medium, means that different levels of digital engagement are possible. The way that the computer is "wielded" brings potential to the conceptual design approach. The design response of a non-digital architect, a CAD using designer, and a designer who knows "scripting" or programming will likely be very different from each other. Each of these practitioners may be able to achieve excellence of design, but their conceptual approach will likely be radically different.

However, what happens in design when the focus of the work shifts from a direct response to a given design problem, to designing a tool (at both a conceptual and pragmatic level) that will resolve (or at least facilitate the resolution of) a problem? This question addresses the approach and understanding of both the problem, but also the creative approach to using tools, and the reciprocal effect on creativity that tools have. This issue is a fundamental question implied in the development and application of the digital chain in design.

4.2.7.1. Determinism vs. instrumentalism

When investigating the role of tools in development, there are two main theories.[43]

The theory of "*technological determinism*" states that the development of technology is a force outside of man's control. In this theorem, one invention instigates the next and that there is no cohesive control over technological development. The lack of control is due to the ability of people to "mis-appropriate" technology, to use it in ways unforeseen. The evolution of technology is driven by the advantages given to those users who are empowered by the tools (including those who adapt or misuse them). In the end, it is this social, economic, and political inequality; granted by the enabling power of the tool, which drives future development of technology.

---

[42] Turing, A.M. (1950)
[43] From: Carr, N. (2010):44-48

The contradicting theory is that of "*instrumentalism*", where it is argued that technology is neutral, and that tools are subservient to their users. A tool is a means to an end, and invokes no goal of its own. This view is more widely adopted, perhaps as users (and especially traditionalist designers) do not like to consider their own control or talent might be marginalized by a technology.

These two theories mirror the debate about the use of digital tools in design: Whether the computer should be regarded as a pragmatic tool, firmly within the control of the designer; or, if the computer and digital tools should be regarded as a medium and a "partner", an ally with specialized skills in logic and mathematics who can be relied upon to provide partial solutions to the objective parts of an analytical design problem.[xix]

4.2.7.2. Design as a search

If the computer is conceived as a computation machine, and its programming is a set of logical instructions, then it is clear that the machine can in no way be considered "creative". A programmed design may result in interesting and beautiful constructs, but these results are the product of reproducible functions, rather than any form of conscious digital intent. Computers, design software, and scripts are all purposefully "designed", and insomuch the results emanating from them are still the subjective resultant of human intervention and design, albeit the design of process rather than a specific design product.

The digital medium has specific advantages of speed and efficiency, but fundamentally lacks an ability for any form of complex subjective design critique. Digital scripts effortlessly produce a multitude of different functional design options, but to discern which one is the most "beautiful" is impossible. As such the computer is better used as a production and "search" machine than it is as a creative machine.

If evaluation criteria are explicitly defined, search heuristics, comparative logic, and performative feedback can be used as a refining method for design development. By using the computer to filter many design results (based on pre-defined search criteria) the workflow is streamlined. The job of the designer remains to make the design decisions, and to choose if further combinations or permutations are required, but the tool allows for a more logically refined set of options.

4.2.8. Design as a language

Language is an intellectual tool, used by societies for the recording and communication of information. Historically, thinking was first limited by the capacity of memory, and knowledge was limited to what you could recall; communicating an idea provided an expanded memory base. Language was the first invention for expanding memory.[44] Further development of language as physical manifestations of information; first through drawing, and then text, allowed for an extension of memory beyond the individual. Complex thought was made possible by the longevity and the compounding of information.

Languages are either natural; "organic" and evolved communication (spoken, signed, or written), or they are artificial: devised for specific purposes. Artificial languages include anagrams, cryptography, mathematics, and computer programming languages.

All languages have *a lexicon* of allowable words (or other tokens) based on an agreed alphabet or sign system; and they have an explicit way of combining those elements legally; *the syntax*. Grammar is the set of rules organising the syntactic components of the language. With a decent vocabulary, and a good understanding of the grammar and syntax, a speaker (or in our case a designer) can synthesize any well-formed sentence in a language. This is "*Chomsky's Dictum*".[45] This dictum can be applied equally to natural or artificial languages, and texts written in those languages can be used to describe new phenomena. This creation of phenomena, can be new communicative sentences and statements, …or in our case architectural definitions.

[44] From: Carr, N. (2010):p.51

[45] See: Chomsky, N. (2002)

If we extrapolate this theorem to an architectural analogy, then ability to define and express architectural form, geometry, and function can all be accommodated within digital algorithmic code. The linguistic dictum applied as a theory for a language of architecture forms the basis for the theory of "Pattern Language"[46]; discussed in the following section.

This combination of explicitly descriptive "language" (code, programming) combined with digital CAD technology is the basis of the generative algorithm. The concept is that as a tool, a generative algorithm is a description of an object; equal to an image, a drawing, a text, or any other form of representation. The primary difference is that, as an artificial language, the architectural product (as instruction sets to builders, or algorithmic sets to graphical programs, or G-code for a CNC production machine…) relies on an additional translator: a technology to interpret it and transform it into a proper representation that is accessible for human comprehension.[47]

4.2.9. Future Tools

Digital design and production tools have significantly affected contemporary design methods. The tools offer benefits, but also challenges; given the constrained logical medium, they impose potential for dissociation for designers, how can such useful tools be problematic?

> *"When CAD first entered architectural teaching, a young architect observed that; 'when you draw a site, when you put in the contour lines, the trees, and other features, the site becomes engrained in your mind. …You come to know a terrain by tracing and retracing it, and not by letting your computer regenerate it for you.'"*[48]

This observation highlights one of the potentials "disconnects" between the designer and design information. Traditional craftsmanship and *reflective practice* both rely on knowledge, skill, and experience during the process of design. Through "working" a problem, the discovery of new information about the problem reinforces understanding, and constantly provides stimuli for the designer's senses, engaging experience and the ability to foresee appropriate solutions. The work process is in itself actually an intellectual tool in the development of a design solution; it is the iterative working that "matures" the design, and also the designer.

Digital systems cannot functionally assist in the conceptualization of design; the main value of CAD is workflow efficiency and speed in the design process. However, this thesis proposes that the constraints of the digital medium force the digital designer to operate in a different epistemological manner. Because the digital medium requires an "explicitness" of design "moves", there is an equal and forced *reflection* on the contextual issues of a design problem, and a longer time developing the precise definition for the design solution. The tool and its constraints cause a different type of *reflection*, but one that can result in a similar degree of understanding and maturity.

4.3. Design Theory[xx]

"*A designer is a planner with an aesthetic sense.*"[49] This statement shrewdly subdivides the practice of design into its two specific components. But design is not a simple addition or overlay, rather design at its best is a homogenous solution of skill, knowledge, and experience of both manual and intellectual process. Excellence of design occurs when the final result cannot be subdivided into constituents.[xxi]

[46] C. Alexander, et al (1977).

[47] From: Coates, P (2010):p.6

[48] Indirectly quoted in: Sennet, R.(2010):p.40

[49] Menari, B. (1966):p.12

Digital technology may be seen as confounding this holistic approach to design, in that the digital medium is at its basis "ethereal" information; constructs of language, code, and syntax, bound by logical functions and processes; however, conceptually these models and output are representations for actual components, processes, and materials. Useful design theory needs to transcend this division and reconcile itself with the realities of the design process.

4.3.1. Praxis and Theoria

In *Form As Thought*[50], Plato differentiates *theoria* from the act of *praxis*, as it involves no "doing" apart from the act of thinking itself. *Theory* in design is the intellectualization of contemplation and speculation, but it also explains actions and phenomena within a bigger process.[51] The simultaneous amalgamation of *praxis and theoria* into the act of design is expounded in Vitruvius's *"De Architectura*".[52]

> *"It follows therefor that the architect who have aimed at acquiring manual skill without scholarship have never been able to reach a position of authority to correspond to their pains, while those who relied only upon theories and scholarship were obviously hunting the shadow, not the substance."*[53]

To be considered "*an architecture*, an additional three Vitruvian virtues are required: *firmitas, utilitas, venustas*[xxii] (solidity, usefulness, and beauty). This inclusion of beauty denotes that the *objective* and *subjective* play equal roles in design, and historically the virtues were incorporated into both *theoria* and *praxis* through immediate and personal *craftsmanship*.

4.3.2. Disconnecting practice and theory

Before the *industrial revolution*, every fabricated artefact was (to some degree) a process of individual craftsmanship. With the advent of industrial machines, production transformed engaged craftsmanship into detached "creative planning" and then "making". Design mutated from an integrated *theoria and praxis*, into an increasingly creative and intellectual process of forethought, followed by the rational and explicitly defined processes of instructed production. The *Taylorist* application of scientific analysis and prescriptive working methods to industrial working methods divided any form of intellectual *theoria* from *praxis*.[xxiii] Through this disconnection, the afore mentioned "*Albertian paradigm*"[54]; *making* became (by definition) wholly predictable; creating a condition where there is no emphasis on creativity, and therefor, minimal potential for *radical* innovation. This loss of symbiosis resulted in a focused and intellectualized approach to design, but a loss of ability for production to directly inform design and significant constraints to creativity.

This disconnection of became a particular focus of design movements in the early 20th century. The design movements evolved due to influence of machinability and new aesthetics of industry. The art-nouveau movement transformed into art-deco, partially driven by the purity of geometrical forms that were more easily machined (thereby allowing for greater industrial productivity). One stated goal of the Bauhaus school was "*to create a new guild of technologically enabled craftsmen, without the class distinctions which raise an arrogant barrier between craftsman and artist.*"[55]

The design innovations commonly associated with the Bauhaus of minimalism, rationality and functionality, and the idea that mass-production was reconcilable with the individual artistic spirit were common to design and art schools, however as western education positioned architecture and design into the contemporary university these ideologies were confronted with post-war rationalist doctrines.

---

[50] Plato; Chapter 4 of *The Parmenides*

[51] From: Turnbull, R., (1998):p.29

[52] Vitruvius.(BC) "The Ten Books of Architecture": Book1 – "The education of the architect"

[53] Morgan, M.H (trans) (1960) "*The Ten Books of Architecture*" Vitruvius: p.5

[54] See quote in section "3.3 Architectural Technology"

[55] W.Gropius, in: Wingler, H.M. (1978):p.23

4.3.3. Design Research

The subjective process of design has always confounded the positivists; in that the base concept of positivism states that all phenomena can be explained through empirical means. Rationalist investigations of complex systems in the 1950s gave rise to the idea that if design could be structured as a set of formal methods of logic and mathematics, then it could be modelled, and solved analytically. The post-war technical rationalist doctrine instituted in most universities promoted this idea in the creation of the field of *design research,* specifically to investigate the application of systematic methods of design.

The primary investigative dilemma was the fact that the decisions are complex and multi-parametric, and that no single "best" answer exists for a design. Influential theories and systematic methods of design emerged from these investigations including: *Morphology of Design*[56], *Pattern Language*[57], *the Systematic Method*[58], and *Design Methods*[59]. Each theory analysed design and methods, and proposed processes for decision systemization. These highly systemized approaches all sought to "demystify" design by turning it into a more "accessible, accountable and transferable process", and they focused on proving that design was an activity of intelligence and procedure, rather than talent or artistry.[60]

In 1972, psychologist, architect and design researcher Bryan Lawson studied problem-based and solution-based approaches to design. Architecture and science students were observed solving design problems where; *the scientists attempted to discover the rules that consistently optimized the design requirements, whereas the architects focused on the best solution possible given the constraints.*[61] Unlike the scientist who must search for many cases to substantiate a rule, the designer can be gratified in simply finding an appropriate result.

> *"Design teams therefore need the freedom to reformulate their design problem in mid-process. … A solution is in many cases impossible to determine. Architects therefore, aim to satisfy rather than optimize."*[62]

The difficulties of objective approaches to design were acknowledged by design theorist John Christopher Jones. In his book *Design Methods*[63], he reiterates that the *ill-formed* nature of design problems motivates a need design flexibility. The design process is a method of discovery and refinement, where the understanding of the problem and its context changes as the process advances. Because of this, Jones criticizes rationalist systematic design methods. He complains of: "*losing control of the design situation once one is committed to a systematic procedure, which seems to fit the problem less and less as designing proceeds.*"[64]

4.3.4. Problems with problems

Empirical and rational problems (ex: mathematics, or scientific hypotheses) have well-defined parameters and methods for their resolution, and it is clear when a problem has been solved. Design problems, by contrast, usually lack detailed information in three defining ways: the start state is typically under-defined, the problem goal is fully open to interpretation, and the transformation methods are unspecified.[65] This lack of specification has led to design problems being categorized as either ill-structured[66] or "wicked" problems[67].

---

[56] Morris Asimov (1962)
[57] Christopher Alexander (1964)
[58] Bruce Archer, (1966)
[59] John Christopher Jones (1970)
[60] From: Alexander, C. (1964)
[61] Paraphrased from: Lawson, B. (1980)
[62] Simon, H.A. (1969)
[63] Jones, J. C. (1970)
[64] Jones, J. C. (1970): p.27
[65] From: Reitman (1964)
[66] Simon, H.A. (1973)
[67] Rittel and Webber (1973)

"In design, problems are wicked in the sense that a design problem and its solution are linked such that in order to think about the problem the designer needs to refer to a solution. Furthermore, there is not an absolute way to tell when the problem has been solved because the referents for such a judgment are dynamic and arbitrary."[68]

Ill-defined problems such as design typically rely on higher-order intellectualization of the problem, such as the use of analogies, design metaphors or abstraction. These methods work because they address both the lack of understanding of the start state, and also provide some expectation and guidance for a result. The processes involve complex cognitive mechanisms, as the design task usually relies on the visual domain, thus involving the usage of visual thinking and *perception* in the cognitive process of design.

A design task is intrinsically related to its solution. If a problem is ill-defined at its outset, then there is no explicit goal to fulfil, but rather the solution is a creative interpretation of the goal-state, made explicit through refinement and the work of the designer; the task is only fully defined by the creation of the result.

When committed to a rational, explicit and systematic process, a designer is not able to adapt the design to changing understanding while "in process". This inflexibility eliminates the chance to react to spontaneous *emergence* of both understanding; but also of results that may be more beautiful than rational. As such, systematic problem solving risks being disconnected from the Vitruvian virtue of *venustas.* When empirically or digitally derived solutions are posited within the frame of *rhetoric* (where design to this day is typically validated), the expressed humanistic *pathos* (passion, beauty and emotion) is, by definition, insufficient to convince an audience of its merit.

4.3.5. Rhetorical critique

Contemporary *design theory;* the intellectualization and explanation of design methods, is a direct appeal to *rhetorics*. Design theory augments the value of a design solution or method by imbuing it with intellectual expression and reference, such that it engages and convinces an audience of the *firmitas, utilitas,* and the *venustas* of a design.

The concept of *veustas*, (*beauty)* is highly subjective and based on perception, but it is subject to historical and cultural bias. In a *rhetorical* process, the designer is balancing the qualities of a design against the needs of a known context and audience, and as such, the designer does have the opportunity to address prevailing cultural and psychological values.

The issues of culture and memory and their role in perception strongly influences in contemporary design theory. The use of analogies, metaphors and abstraction as instruments for design assist in engaging the critical audience. Understanding perception is a tool to allow for greater understanding of the psychological processes of design development.

4.3.6. Gestalt theory

The mental ability to interpret patterns and the process of conceiving abstract relations has developed as *gestalt philosophy,* and has been used to validate design theory.

Gestalt theory developed through application of *systems theory*, *cybernetics* and neurology to help explain the holistic concept of perception. The theory proposes that the act of viewing invokes *memory* as a form of mental feedback. This memory-feedback combines with the visual input to form a perceptive understanding of a scene that is "*other than the sum of its parts*"[69]. This mental process allows a viewer to rely on experience and memory to complete under-defined contexts, and to understand situations where information may be incomplete or poorly presented.

---

[68] Restrepo, J + Christiaans, H. (2004)

[69] Attributed to: Koffka, K. (1935), *Principles of Gestalt Psychology*

Perception proposes that the brain uses the concept of *emergence*, the simple overlay of many bits of information and the rules that govern them, to create a more complex understanding. Perception is also augmented by three interpretation principles of: *reification, multistability* and *invariance.* [xxiv] These deciphering "instincts" invoke perceptions of geometry from incomplete or ill-defined patterns.[70] This ability of pattern recognition is beneficial, both perceptually and conceptually, in the structuring of a design.[71]

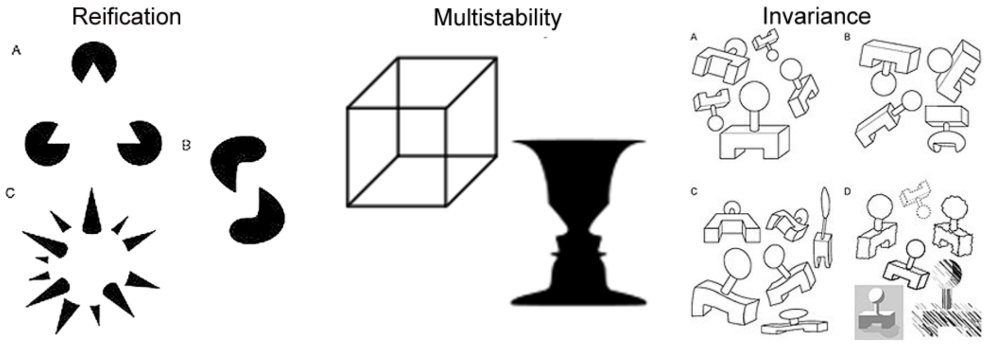


Fig.4.3.6. Components of Perception: reification, multistability and invariance

This skill of perceiving patterns, elements, and associations can be trained. It is based on improving the skills of recognition, but also on *repertoire*. Practitioners develop perception by improving visual memory through a repertoire of images, ideas, examples and actions[72]; and then draw upon these to makes sense of unique situations. Familiar situations function as precedents or metaphors, which allow an ordering of an ill-formed problem. This form of deductive perception is central to *reflective thought*.

4.3.7. Reflective Practice

> *"As designers, we think through doing. Design is a reflective practice between the designer and her design materials. When you sketch something and commit it to paper, it moves from being an abstract thought to something that is more concrete and real. Perceiving this concreteness, in turn influences thinking, leading to new questions that spawn new ideas..."*[73]

The theories of *Reflective Practice,* developed in the let 1970's by MIT Professor Donald Schoen and collaborators; shifted focus from the processes of design onto the actions of the design *practitioner*. The theory is a counterpoint to technical rationality; in that it relies on logic, but it acknowledges an intuitive and tacit "*knowing in practice*". The concepts and methods developed in *Reflective Theory* are now recognized among the most significant and comprehensive theories of design methods.[74]

4.3.7.1. Iteration

> *"As a design progresses, the situation "talks back" and the information is used to reframe the situation once again. The unique and uncertain situation comes to be understood through the attempt to change it, and changes through the attempt to understand it".*[75]

The central concept of *reflective theory* is that design progresses as more information is revealed about the problem. The theory states that design is a series of iterative loops, with

---

[70] From: Tuck, M (2010)
[71] From: Restrepo, J + Christiaans, H. (2004)
[72] From: Schoen (1983):138, Dewey, J. (1933):123
[73] Dane Petersen: http://brainsideout.com/
[74] Oxman, R.(2005):101; N. Coats (2011):22
[75] Schoen (1982):132

each cycle going through steps of *analysis, evaluation, reflection and synthesis*. The cyclical process, at the problem level, focuses on resolving design issues and parts, while at the overview or "meta" level, the process focuses on gaining experience, followed by consciously applying that experience.

This continual learning while *in* practice allows for informed *reflection* on the design at hand and on the methods being used. Because each design cycle is quick, direct, and also distinct, the structure for designing can be manipulated to suit the interpretation and subjective decisions of the designer. "*The theory accepts that the complex nature of 'what goes on in the designer's head' is an intellectual but individualistic process.*"[76] Schoen describes the steps of this iterative method as "*naming, framing, moving, and reflecting*".

4.3.7.1.1. Naming

Reflective practice proposes that design is inherently non-positivistic, in that it comes from the application of experience and intuition on top of logical appraisal and reaction. For Schoen the root of design is an *unquantifiable* reaction to situations that come from mental pattern matching: In this way the first process, "*naming*" is a direct analogy to *Gestalt perception*. For Schoen, the act of *naming* is a wilful act of defining and committing to an ordering mechanism, and giving the problem conceptual starting point.

4.3.7.1.2. Framing

Once a problem is *named,* the boundaries, components, relationships, and coherences are then (loosely) defined by *framing*. Naming and framing combined are the *setting* of a problem, the imposing of a structured coherence upon it "*…which allows us to say what is wrong, and in what direction the situation needs to be changed. Problem setting is a process in which, interactively, we name the things to which we will attend, and frame the context in which we will attend to them.*"[77]

The act of framing is acknowledged by Schoen as "*an improvisation; inventing, testing and refining strategies in order to gain further insight into the problem, with the goal being to provide coherence and a structure to the overall problem.*"[78] Design researcher John Dewy describes this initial clarification as "*the problematic: the problem of problem setting.*"[79]

Determining *the problematic* is highly interpretive, and the *setting* of a design is the point that creates significant distinction between the works of different designers. The *setting* of a design is also the fundamental confounding challenge to any techno-positivist approach, as without interpretation and association the problem becomes purely rational.

"Those who hold conflicting frames pay attention to different facts and make different sense of the facts they notice. It is not by technical problem solving that we convert problematic situations into well formed problems; rather, it is through 'naming and framing' that technical problem solving actually becomes possible."[80]

It is professional skills and capabilities of perception that enable the reframing of problems such that they better fit a practitioner's abilities.

Framing a design problem occurs cyclically throughout the design. The working process provides constant and evolving insight into the conditions, context, and complexities of a problem, and this insight is consistently merging with memory to create new perceptions. As the project evolves the problem becomes refined, and so too does the solution method.

4.3.7.1.3. Moving

"Moving" is Schoen's name for the small experiments and testing undertaken within a single design loop. There are three different types of testing.

---

[76] Lawson, (1997)

[77] Schoen, D. (1987):40

[78] From Schoen, D. (1987):5

[79] Dewy, J. (1938).

[80] From Schoen, D. (1987):5

- *Move-testing experiments:* testing localized cause and effect with no specific goal.
- *Hypothesis testing:* experiment to affirm or negate an intended reaction (hypothesis).
- *Exploratory experiments*: exploring with no goal except to gain understanding.

Each test is a local design experiment, contributing to the global task of reframing the problem and evolving the design. As the designer iteratively works the problem, and instinctively reflects on the consequences of moves, he is aware of the implications, and forms new understanding to guide further moves"[81]

4.3.7.1.4. Reflecting

Reflection is cognitive feedback of the designers experience and knowledge to the design process. Schoen differentiates two forms of reflection as *reflection IN action*, *reflection ON action*, and *ladders of reflection*.

Reflection-in-action is analogous to 'thinking on your feet'. It occurs within the design process, and involves looking to experiences, knowledge, and intuition, and using these to attend to the design and theories in use. It entails building new understandings while in the process of design, so as to inform the actions in the situation that is unfolding. "*When a practitioner reflects-in-action in a case he perceives as unique, his experimenting is at once exploratory, move testing, and hypothesis testing. The three functions are fulfilled by the same action; from this fact follows the distinctive character of experimenting in practice.*"[82]

Reflection-on-action comes after a design solution has been proposed, and occurs while the design problem is being refined and also after the final solution has been put forward. In *Reflection-on-action* the practitioner removes himself from the process and allows an overview of the process. He reflects on the phenomenon before him, and on prior understandings, which have been implicit in his behaviour. He evaluates the process to see if it has achieved expected results, or if it is diverging from them, the determinations from such introspection is then formally positioned into a designers experience and intuition.[83]

Ladders of reflections are the cumulative amalgamation of experience. The act of solving a problem adds to experience and intuition of the designer, making the ability to solve future problems a positive feedback loop. This iterative cycling is called a *ladder of reflection*, where the products of reflections also become the objects for further reflections.

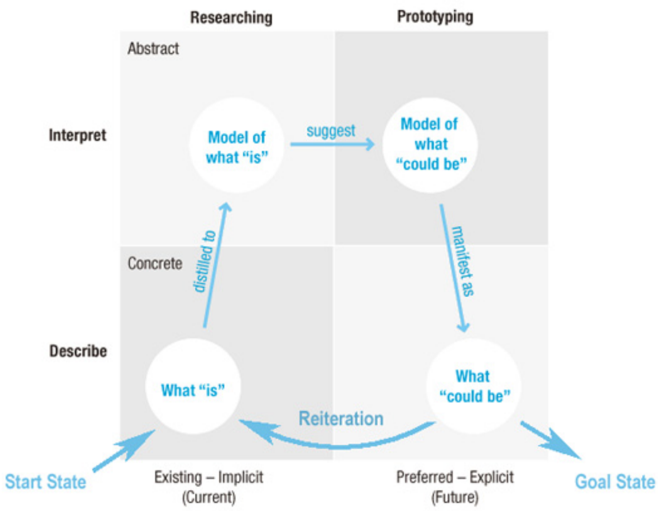


Fig. 4.3.7.1. The Analysis-Synthesis Bridge Model. This model for the iterative development process depicts the different questions asked of the design, and the formal processes involved in each phase. (Source: Dubberly, H. et al. http://www.dubberly.com)

[81] From: Schoen, D. (1982): p.94
[82] Schoen, D. (1982): p.147
[83] Schoen, D. (1983): p.68

4.3.7.2. Iterative looping

The process cycle of *analysis, evaluation, reflection and synthesis* provides insight and momentum for a design process. Although each of the steps may be creative and intuitive, the overall process is still systematic and procedural (as can be seen in the analytical diagram of the "Analysis-Synthesis Bridge Model": Fig.4.1.10.1.4). Each phase of the cyclical process can be seen to incorporate a balance between opposing acts of: interpretation and description, and analytics and synthesis. The looping of the design cycle shifts from the concrete to the abstract and back again.

At each point in the process, the designer must commit both himself and the methodology, to a decision, what Schoen calls a "stance": a position taken with regard to a specific problem. A "stance" is a position of theory, and one that validates the design decisions being made and the vector and progression of the design process. It is used to explain or justify the current *problematic*, and to motivate the next iteration.

4.3.7.3. Reflection as feedback

Pioneering digital artist, Lionel March distinguishes a designs mode of reasoning as being different from logic and science. "*Logic has interest in abstract forms, science investigates existent forms, design INITIATES novel forms*." March goes on to state "a scientific hypothesis is not the same as a design hypothesis, … a speculative design cannot be determined logically, because the mode of reasoning involved is essentially abductive"[84].

Reflective Practice differs from the *scientific method* in that the practitioner is free to engage and mediate the process so as capitalize on unforeseen opportunities and to manipulate results for specific goals. The designer is not a *neutral observer*.

Reflective Practice demonstrates that design is analogous to *second order cybernetics: The designer changes the design, however the process of designing also informs and alters the approach, knowledge, and skills of the designer himself.* The ability of the designer to "step away" and get an overview of the process demonstrates that *reflection* creates different *orders* of engagement. "*To move 'up' to a meta-view is to move from concentration on an activity, to reflection upon that activity*."[85] As a solution method *Reflective Practice* incorporates iteration, feedback, and interpretation to manage the complexity of open systems. The application of such a systematic method has the advantage of guiding and justifying subjective processes, but is still able to maintain the credibility of the design solution.

4.3.8. Contemporary theory

"*Many design theorists propose that traditional methods of design-by-drawing is becoming too simple for the growing complexity of the man-made world*."[86] This statement was written in 1970, with the belief (and concern) that systematized design would become prevalent; however, design remains resistant to rational process, and continues to be validated by *rhetorical* critique.

Design computation has had significant influence on the theoretical and cognitive approaches of designers.[87] As is characteristic in periods of cultural change, significant theoretical writing have attempted to re-address key concepts of past architectural and theoretical discourse[88]. The digital medium has bestowed a new set of ideas and a unique conceptual platform for the transformation of architecture as a design discipline.[89] As an intellectual pursuit, the combination of design theory and the digital medium has increasingly invoked concepts of analogy, metaphor, and also modern philosophy[xxv]. Abstraction is by definition analytically

---

[84] Lionel March, as quoted in Cross, N. et al.(1996): p.196

[85] Schoen, D. (1987): p.114

[86] Jones, J.C. (1970): p.27

[87] Knight, 1999; Knight and Stiny, 2001; Ozkar, 2007

[88] Kipnis, 1993; Lynn, 1993 and 1999; Kwinter, 1998, 2001.

[89] Liu, (2006); Reiser and Umemoto, (2006)

irrational, but it is such free-association that often enables *design theories*, which in turn are used to validate experimental design.

Among theoretically significant practitioners of the early digital period are Cache[90], Lynn[91], Van Berkel[92], Oosterhuis[93], and FOA[94]. Rather than architectural strategies of combination and transformation, their processes focused on performative, and topological investigation of complex geometries. In many cases "form" was ideologically derived, but as the technology has evolved there has been a stronger bias towards performative process and generation strategies, leading to increasingly rational design theories. This differentiation between *digital form* and *digital processes* is amplified to this day, and contributes to the *emergence* of new conceptual vocabulary of performative design, and this characterizes what might legitimately be considered the early formative stages of a paradigm-shift.

4.3.9. Future Reflection

Reflective Practice was developed in the context of paper-based media as a "*dialogue with the materials of the problem.*[95] Any new design theory must now move beyond static representation, and challenge the theory and praxis from a "meta-view" that includes technology. The liberation from paper-based designing allows for a more conceptual, intellectual, and methodological theorization of design conception: one based on systems thinking and associations rather than composition.

From the many points of subjective intervention in *Reflective Practice* that have been identified; it can be concluded that the current explicit and objective nature of computation and programming are unable to make *reflective* associations. However, the iterative looping process, logical operations, and parametric composition of *Reflective Practice* show great similarity to the structures and methods of algorithmic programming. The essential differences between *Reflective Practice*, and algorithmic programming however remains the *setting* of the problem and the process of abstracted *reflection* occurring within the each cycle of the process.

This thesis, as part of its overview of digital process, seeks to observe if *Reflective Practice* is still a dominant theory and model for design methods, or if the process of theorising in digitally mediated architecture has changed. If design "as reasoning" is conducted through exploration and manipulation of graphical symbols, does the logical and constraining (but still highly visual) medium of digital design alter the designers understanding? Going beyond the 'backtalk' from visual images, the digitally compounded processes of *formation, generation and performance* may create a novel understanding of "informed" design that justifies a new mode of working design; *a digital reflection*.

---

[90] Cache, B. (1995)

[91] Lynn (1999)

[92] Van Berkel and Bos (1999)

[93] Oosterhuis (2002)

[94] Zaero-Polo and Moussavi (2003)

[95] Schoen and Wiggins, (1988)

Endnotes:

---

[i] Note: The use of the word "*Architectural*" in this context is taken in the structural and holistic sense. Although confusing in a thesis dealing with *building architecture*, the term is common in industry, programming, and organization. Please excuse the duality of meaning and any confusion caused.

[ii] Attributed to Socrates - by Plato in *"The Socratic Dialogues", from:* Turnbull, R., (1998) *"The Parmenides and Plato's Late Philosophy".*

[iii] All scales of known phenomena of that time

[iv] Architecture is often defined as a *holistic* enterprise, implying an all-inclusive design perspective. This trait is argued to be appropriate due to the multitude of constraints, regulations, and contextual parameters involved in resolving projects. From: Holm, Ivar (2006). "Ideas and Beliefs in Architecture"

[v] Von Neumann: is credited with inventing both the idea of the general-purpose computer, and the concept of cellular automata.

[vi] Used by Plato in "the Laws" to signify self-governance

[vii] Concepts that eventually enabled Bell Telephone Laboratories engineer Harold S. Black to develop the use of negative feedback signals to control noise in early telephone systems.

[viii] The paradox of observing a system is that one changes the system by observing it. See: http://en.wikipedia.org/wiki/Schrödinger's_cat

[ix] Predecessor to the MIT Media Lab.

[x] Ex: the facade from Jean Nouvel's *Institut du Monde Arabe*, active earthquake suppression systems, or the concept of "smart homes".

[xi] A thought attributed to Norbert Wiener in Kurzwiel, R. (1992). p.460.

[xii] This is called the "Pauli exclusion principle" which explains why subatomic particles cannot occupy the same quantum state, and therefore if they exist they must take up physical space. See: http://en.wikipedia.org/wiki/Pauli_exclusion_principle

[xiii] Extrapolated from: Michael Wienstock "Can Architectural Design Be Research?" AD Article.

[xiv] Instrumentalism: the view that a theory is a useful instrument in understanding the world.

[xv] Psychology term coined by the Belgian sociologist Daniel Warnotte, meaning a tendency to look at things from the point of view of one's own profession rather than from a broader perspective. Ref : http://en.wikipedia.org/wiki/Déformation_professionnelle

[xvi] To examine this metaphor more extensively see "The Blue Brain Project", a major research initiative at the EPFL. Ref: http://bluebrain.epfl.ch/ (accessed 2010)

[xvii] For comparison this paper is being written on a computer equipped with an Intel i7 CPU. This CPU is equipped with 714 million transistors. A human brain has approximately 21.5 Billion neurons. Neurons and transistors are in no way equivalent, but the human brain is still far more complex, robust, and neuron the clock speed and frequency rates are faster.

[xviii] Moore's Law : The number of transistors that can be placed inexpensively on an integrated circuit doubles approximately every two years: http://en.wikipedia.org/wiki/Moore's_law

[xix] This issue is discussed in detail in the discussion section "7.3 Computer as Partner"

[xx] It is acknowledged at the offset of this section that there is no definitive definition of design, nor do clear rules or methods exist for design processes. Due to the subjective nature of design methodologies, it is understood that this section is addressing generalities of *design theory* and its relationship to technology.

[xxi] From: J.Smuts (1927): p.140.,In *Holism and Evolution,* Smuts compares "creativity" in mechanistic and holistic approaches to discoveries in chemistry.

[xxii] The Vitruvian definition of *venustas* is beauty, but one specifically defined by order, nature, and geometry.

[xxiii] See section 2.4.2. Industrial Optimization.

[xxiv] For definitions see the glossary.

[xxv] Examples are numerous and bi-directional: Eisenman and his musing on Derrida and *deconstructivism*; Lynn, Kipniss, Reisers (and many others...) interest in the spatial philosophies of Deleuze and Guattari, DeLanda's engagement of philosophy with architectural theory, DeBotton's critiques of performative justifications in architecture...

5. Practical Investigations

Architectural design combines theory and practice. The following work investigates digital design and production technologies to determine if they are implemented simply as practical tools, or whether their potentials alter the intellectual and conceptual act of creativity.

Creativity is expressed in in conceptual and formal decisions, but also in the hierarchical development of the project. If a project is viewed as a methodological process, then design resulting from digital tools will be defined by how the user deals with the abilities and constraints of the chosen technologies

Conceptually, a design is populated with the *components* of a specific problem, and data becomes the medium for their *relationships*. The underlying concepts of *data transmission, translation,* and *continuity* all permit connections between stages of the digital chain. Data defines the linkages in the overall process, and as such the previously stated definition of the *information machine* and the three basic abilities of *Control, Prediction,* and *Processing,* will facilitate the understanding of how to use the tools of design. As such these "abilities" will be used as a categorization topics for the investigations.

Control is defined as the ability of the computer to use logic and mathematics combined with explicit programming to manage data and return a desired solution. To investigate *Control*, several projects were devised that examine the manipulation of data across different platforms, with a main emphasis on the use of digital image analysis and control programing. Designs that link image data to complex design structures are tested to see if digital abstraction can be used as an efficient and intuitive means of controlling complex systems.

Prediction investigates the use of design and behavioural modelling to simulate interactions. Two independent forms of models for this are required; the *design model*, and the *behaviour model*. To investigate *prediction* as a part of the digital chain a project was devised following a simplified *scientific method*; predictions were developed using digital tools, and then were validated with physical testing. The resulting knowledge was then used for a digital design and production project.

Processing, as the final category of investigation is the most complex level of computationally mediated design. It combines tools and technologies with cybernetic feedback loops to deal with *problems of organized complexity*[i]. The investigation for this section sought to develop a simplified "bi-directional" digital chain, where the technologies still allowed for creative design within of an optimized system.

These three functions of the *information machine* are used as a categorization system to organize the investigations undertaken over the course of the thesis. Each categorization is not exclusive, as the investigations and projects may actually have some of the overlapping characteristics from the other categories. The goal for the classification however, is to allow for progressive evaluations and conclusions about the digitally mediated processes and their affect on the architectural paradigm. Each set of investigations reveals how the concept of the *information machine* can be used to manage complexity. This understanding, combined with the previous theoretical research, should allow for an informed assessment of the future of digital technologies and the digital chain in architecture.

5.1. Objectives

> *"Schools of architecture occupy a middle ground between professional and art schools. Architecture is an established profession, charged with important social functions, but it is also a fine art; and the arts tend to sit uneasily in the contemporary research university."*[1]
>
> – Donald Schoen

[1] Schön, D. A., (1990):p..18

The overall thesis objective is to understand new linkages between technology and creativity, and to use this knowledge to determine if digital technologies can be considered a new *paradigm* in architecture.

Design is a combination of objective process and subjective artistry. Objective process can be learned by study; however, the development of artistry depends on a freedom of practice and guidance of practiced oversight. If we accept the doctrine the Bauhaus School[ii], then the process of fostering artistry is not to teach it, but is to provide guidance to students to help them *recognize* their own expressions. This *recognition* is the skill that is being taught, and with experience it evolves into "reflection": self-criticism supported by experience and insight.

Practitioners who are viewed as superior to others do not necessarily have more knowledge or better skills, but rather it may be simply that their "wisdom" allows them a privileged insight to a problem. This advantage does not come from skills of evaluation, but rather from the way that the problem is framed and developed; practices that come from experience rather than knowledge. Once a problem is innovatively framed, intuition, artistry and skill can be engaged to artistically resolve the problem.

The investigative work of this thesis investigates the disconnect between the subjective process of design and the objective medium of digital technologies. For this to be effectively undertaken a new form of *wisdom* needs to be established such that *reflection* is possible.

5.1.1. Hands-on

> *"Skill is trained practice; modern technology is abused when it deprives it users precisely of that repetitive concrete, hands-on training. When the head and hand are separated, the result is a mental impairment – an outcome particularly evident when a technology like CAD is used to efface the learning that occurs through drawing by hand."*[2]

Real world design problems are ill-defined and a complex combination of parameters, both of design, but also of "making". Computers and digital design programs require explicit well-formed definitions for their solution processes. The ability of a designer to be explicit about a design problem is limited by their knowledge and experience. For this work to be pragmatic the investigators need an adequate experience with technology and the processes of "making".

Over the past century the role of the architect has transformed itself from the "master-builder", working daily on the construction site with all of the trades; into the "architect", typically found in the design office. The overall knowledge of construction, and personal experience of "making" continues to decrease,[iii] however the tangible issues of materials, assembly, and construction are still major design considerations. Given this, one goal of the *practical investigations* in this thesis, is to provide "hands-on" experience with the digital chain in architecture.

The real world experiences of "making" with real materials, digital fabrication machines, and full 1:1 scale construction will provide the required *digital experience and insight* such that the investigators will be able to define the technologically mediated *problematic,* and then be able to proceed with a justified digital design strategy. This *hands-on* approach is intended to balance this thesis within the Vitruvian definition of architecture, addressing both theory and practice. The practical investigations are used to establish both *concepts* and *proofs of concept* for digital tools and strategies; but they are also used to demonstrate how the use of technology broadens the intellectual approach to information, associations, and the concept of systems within design.

5.1.2. Investigation objectives

For the overall thesis investigation into the paradigm of digital technology and its current position in architectural practice, the investigations are based on a different, but complimentary, set of objectives.

---

[2] Sennett, R.: p.52

There are three main practical objectives for the investigations:

- Operation of technology: The first level tasks were to learn about the different technologies, how they integrate into a digital chain, and how to engage the digital chain in projects. This objective is focused on skill building, such that higher objectives can be investigated.
- Adoption of technology: The second level of investigation is to gain insight into how technological understanding changes *the problematic*, and the processes of architecture, and what obstructions exist preventing wider adoption.
- Theory and technology: The final and most conceptual level goal was to determine if digital technologies, and their inherent characteristics and constraints have a specific effect on architectural theory, and how conceptions of design and architecture change due to technology.

5.1.3. Collaboration

A supplemental purpose for the project work was to demonstrate the potentials of such technologies to a wider architectural community. Although digital design is used extensively in practice, most local firms do not have access to digital production and fabrication machines. Through demonstrating the capabilities of the digital chain, there was a secondary goal of developing collaborations and partnerships with practices and industry.

Through these contacts with industry, the investigators in the thesis were exposed to the "current practice" levels of various external commercial firms, including architectural practices, engineering consulting, building material fabricators, material suppliers, and large construction contractors.[iv]

5.1.4. Thesis objective

This thesis has thus far investigated the context and theory of technology and its use in architecture. Given that the primary inquiry of the thesis is to determine the extent to which digital technologies have infiltrated and affected contemporary practice, it would not be complete without practical investigations.

> *"Good design: Fulfils its function, respects its materials, is suited to the method of production, and combines these in imaginative expression."*[v]

At the level of the thesis investigation, the following practical investigations should provide investigate the concepts of "good design" using technological processes. As such the investigations will be reviewed for evidence on three main issues:

- To produce educated conclusions about the impact of technology on the architectural workflow.
- To examine the ability for trained architects and designers to adapt to new technologically mediated practices and theories of design and production.
- To examine whether the potentials of the computer as "information machine" are being effectively translated into architectural practice.

The *practical investigations* of this thesis should provide substantiation as to whether the concept of the *digital chain* is useful for good design, and whether it is causing a paradigm-shift in architectural practice.

5.2. Methodology

At the fundamental level, these investigations afforded "hands-on" experience with various software programmes, data structures, and machines; providing practical knowledge and credibility for the investigators. At a broader "meta-level" the investigations revealed a summary of issues and findings associated with the learning of new technologies and putting them into practice. These findings are the basis for making general conclusions about the state of the contemporary digital architectural practice.

5.2.1. Approach

The main investigative method was to; define a general *design topic* for the project, introduce and define technologies available for investigation, and to give some specifications (either focused or unfocused) for the investigation goals.

For all projects, the emphasis was placed on the development and refinement of *process*, not on product. The intentions of each project were always the to conceive novel design concepts and production methods. Attention to process meant that the working context was seen as a "research and experimentation laboratory", rather than as a "design studio". Observing the work provided the principal investigators with perception on the learning and development of skills with digital technologies, and insight into the problems of integration into practice.

5.2.1.1. Types of Investigation

To ensure that the adoption of technology was tested under different conditions, a variety of methods were adopted from *design theory*. Three forms of investigation were used which relate to as models over the course of the thesis: *Focused, Unfocused* and *Coordinated*.

5.2.1.1.1. Focused investigations

Focused investigations are *experimental* in that they followed a (simplified and abstracted) version of the *scientific method* with the goal of examining a specific theme, topic, or technology. They state a design hypothesis, and the process of developing the project either proves or disproves the stated hypothesis. Focused investigations were undertaken both in courses (using the students as investigators) and in specific research projects.

5.2.1.1.2. Unfocused investigations

The "unfocused" research methods are *exploratory,* in that they are loosely directed investigations into specific themes and technologies, but one where the *goal state, method*, and even the *start state* need not be explicitly defined. Development methods of *strategy, search, and exploration* were used, as all specifically engage *reflection in action.* Schoen describes this process as: "*not to see what you get, but to see if you like what you get.*"[3]

Unfocused investigations were used in both courses and professional projects, typically in the initial development phases.

5.2.1.1.3. Coordinated investigations

Coordinated investigation methods are used when either the technologies OR the goals are stated, but where the methods are not. The primary focus is placed on project and data management with an emphasis on maintaining design flexibility and creativity, while the secondary design is the process itself. *Reflection on action* provides an overview and *Reflection in action* examines innovations of both the components and their relations within the larger system.

This method is typically subject to specific constraints, however it can be used to develop and coordinate large, complex and a multi-phase projects, or larger scale team projects.

5.2.1.2. Design testing

For the purposes of this thesis four design "testing" models were adapted that use the iterative methods of *Analysis, Evaluation and Synthesis*. These methods were first used to develop design *the problematic* for given design problems, but were used iteratively as well to resolve small "move testing" situations within projects.

The first model is an analytical model based on a simplified version of the *scientific method*, and the exploration models are derived from the three "testing" models of *Reflective Practice*: Hypothesis testing, Move-testing, and Exploratory testing experiments. Each model was revised for use in architectural design, and then to examine how they should evolve in technologically mediated design.

---

[3] Schön, D. A., (1990):p.71

5.2.1.2.1. Design as Planning

Planning is a method of *focused investigation* using a specific plan for action. The goal state is not predetermined, but is developed through strict application of rules. Planning requires that a problem be well defined, that it has a clear start state, that it is bounded, and that the method is clearly specified, as such this process is not exploratory, but is limited to well-formed problems.

5.2.1.2.2. Design as Strategy

Strategy is a determined but flexible plan for action. Strategy requires a well-formed start state and a conceptual goal state of a problem, but does not have an explicit method. Testing makes small, explicit, and experimental steps that are evaluated to see if they move the solution towards the expected goal. The method is flexible but highly coordinated. Strategy does not have an explicitly defined goal, but rather a defined acceptable range of solution; as the problem is worked it becomes better defined.

5.2.1.2.3. Design as Search

"*Frei Otto supposedly once said: "I do not design, I search"… If one truly is looking for novel design approaches, it is unlikely that they can be designed in a predictable manner. Design emerges through the increase in understanding of a design problem and its constraints. To search means to ask the right questions and formulate the framework accordingly.*"[4]

Search is first a process of divergent finding, and then a comparative process of filtering and refining. The method engages abstraction, metaphor and analogy in developing the testing model. Search is a major challenge, as abstraction reinforces state of poorly defined bounds of a problem, implying that the search space is equally unbounded. It is the (often subjective) constraining of a problem by the designer that allows for efficient search. In digital programming "search" is also an optimization method to find minima or maxima in an equation with the minimum number of steps. A number of algorithmic approaches have been defined including: binary, adaptive, stochastic, genetic algorithms, and simulated annealing.[5] These refinement processes were conceptually applied to design methods to refine abstraction and direct design development.

5.2.1.2.4. - Design as Exploration

Designing as exploration recognises that necessary information required to define and structure a designs is not always available at the out-set of a project. Exploration uses small experiments of the problem parameters to develop greater insight and understanding of the problem, and thusly the ability to structure the problem for solving.[6]

The ability of parametric tools to generate alternatives and evaluate their suitability can be characterised by the four forms of designing planning, strategy, search, and exploration or any combination thereof. Understanding the design work-flow as a constant flux between formulation, synthesis, analysis and evaluation represents the typical workflow design.

5.2.2. Digital skill building

The investigative work for this thesis was undertaken either by the author and collaborators, or by students taking a *Diplom Whalfach Arbeit* (ETHZ) or *Unitée d'Ensignement* (EPFL) course. These courses were offered at the *masters* level, so it can be assumed that both the participants and investigators all have skilled experience in design.

All participants had some level of digital experience. The principal investigator and collaborators have extensive knowledge of digital design, computation, programming and digital fabrication and production. Course participants (student investigators), presented a wide range of experience: from basic CAD and image manipulation skills, to full modelling, and programming abilities.

---

[4] Kilian, A. (2007) :p.109

[5] Raphael, B., Smithc, I. (2003)

[6] Logan and Smithers, (1993).

At the beginning of each course a generalized survey was given to evaluate the skill level with digital technologies. All participants can be assumed to have (roughly) equal design skills; developed to the (common) “masters” level, as such individual discrepancies in technical competence could be attributed to experience, skill, and “digital aptitude.” Likewise at the end of each course a concluding (course specific) survey was given, recording opinions and feedback on the investigations.

5.2.3. Technological methodology

The investigations of the digital chain focused primarily on digital design and digital production. For the efficient combined “Integrated Manufacturing” processes it is beneficial to know which machines and production technologies will be used already in the design phase. The various investigations used different digital tools, software, and machines; and in each case the technologies were explicit, and explained in advance. Consequentially the design could also engage the production technology as a “creative” potential. The emphasis of observation was however not on the technology itself, but rather was to develop a better understanding of how the practitioners adapted themselves to technology.

5.2.4. Design method objectives

There were five main tasks in the practical thesis investigations of the digital chain:

- The first task was to develop technical skills of using and exploring digital tools.
- The second task was to foster conceptual understanding of advanced tools and conceptual methods of digital design. The goal here was to introduce “systems” concepts of associative components and tools, and to develop an understanding of complexity of a design and how it can be controlled using digital tools.
- The third goal was to introduce computation tools of scripting and logic algorithms, such that the design becomes more automated and controlled, but that the *problematic* (the meta-design) is still a creative and subjective process.
- The fourth task was to introduce the tools of simulation, evaluation and cybernetic feedback of data into algorithmic processes. This allows for potential higher *orders* of design, and for responsiveness to stimuli and contextual or environmental factors. The conceptual goal is to include prediction such that it informs design decisions, and to enable faster (and potentially more) development iterations in the design process.
- The final goal was to develop an understanding of data structures; and specifically how to manage and transform data to be used across the full range of the digital chain.

5.2.5. Digital Production

Digital production was used for two primary purposes: prototyping and fabrication.

- Digital and physical prototyping facilitates comprehension and allows for testing of geometry and production method.
- Digital fabrication is the 1:1 making of a design, using the final chosen materials, methods, and technologies, undertaken as final production of the design piece.

There are four main parameters that readily affect the optimization of fabrication that should already be addressed at the design phase:

- *Materiality:* The material, structural and aesthetic characteristics, any chemical or physical interaction and its machinability.
- *Machining parameters*: Once material and production machines are known, additional design potential can be achieved by manipulating the operational parameters.
- *Generation of the fabrication data*: Numerical Control (NC) code can be refined, manipulated, or creatively altered for expressive or optimization purposes.
- *Production strategies*: Knowing the interactions between material, machining, and assembly methods, allows for strategies of optimization of geometry, production and time.

5.2.6. Practical Investigations

The methods of design and production developed for the following investigations focus on the digital chain and the abilities of designers to engage with it. The list of projects was developed over a research period of several years, and as such many of the processes and technologies are themselves no longer novel, however the observations of technology and designer interactions are eternally relevant.

The methodology of investigation in all cases focused on stimulating the investigators to build novel design experiences. The challenge was to show that technology could be used for productivity; but with practice and ability to prove that it can also evoke creativity.

5.3. Control

The increasing awareness of "interconnectedness" within our contextual systems (social, environmental, economic…) means that man is turning more and more to technology to manage information in daily life. More information requires more information processing, and this augmentation leads to increased technological expectations in a positive feedback loop. As technology improves so too do the expectations for them to manage the increasing complexity and to control context.

The computer is a device for management and control of information. In its simplest form it requires a set of input data, which represent the problem; a set of programmed rules, which define the solution method; and a goal state and mechanism to transmit this to output. The fundamental power of the computer is the speed at which it can process simple operations. When performed repeatedly, this translates into the ability to manage massive quantities of data and control solutions.

For the purposes of this thesis, however, the focus lies not in singular logistical processes, but in the addition of many "output mechanisms" composed to make up a "digital chain". When appropriate mechanisms are connected in series, the output from the explicit digital processes is highly directed, highly valuable, and is also logically controlled. This thesis focuses on how designers are able to structure problems and use devises, such that the output is well represented, and valuable for use in architecture. Such solutions typically take the form of geometry (represented as either graphics or diagrams); as well as output in the form of mechanical instruction code for fabrication machines (typically represented as text based G-code). The computer, through management and logical processing of data into solutions, is able to control a multitude of processes and machines within the Digital Chain.

The concept of *digital control* is the simple ability to record, store, manage, retrieve, and use large amounts of data to provide useful output results, and for this to be engaged effectively, a designer requires some small comprehension of data structures and computation. The following projects aim to investigate these data structures and processes, and to experiment with the use of "control" mechanisms for expressive and creative design work in architecture.

5.3.1. Ornament Investigations[vi]

The first series of investigations focus on the capability of the computer to assist in the management of design problems. The investigations are gradual in their approach to overall complexity, but as they evolve the emphasis shifts from a purely pedagogic approach, into a creative and expressive exploitation of digital "control" for use of the professional designer.

Ornament as a craft has a longstanding tradition in the history and theory of architecture, but has a contentious relationship with technology and modernity. This multi-faceted relationship provides an interesting context of practice and theory, and delineates ornament as an ideal topic to take as a reduced, isolated, and abstracted topic for design investigation.

In choosing ornament as a topic, the development of design and methods were not constrained by strong functional requirements, and as such the investigations could be conceived as an initial "testing ground" for both methods and machines. Due to the typically subjective nature of ornamentation, the investigators and their work could be free to explore the use of digital tools without the persistent need to justify or optimize each design decision.

Ornament can never be reduced to a question of function; It would be better to say that ornament *may* function, but the motivations for its forms are irreducible to functional or material foundations. The work therefor focused on the ethereal and subjective interpretation of beauty and *delight*, while still addressing the important issues of geometry, aesthetics, individualism, and the eventual transferal of design to production materiality.

5.3.2. Digital Ornament

The development of “digital ornament” challenged the traditional relationship between design and the dependency on skilled workmanship for the fabrication of beautiful and complex products. When working purely in a digital medium, the lack of physicality allows an ease of geometric manipulation and the development of non-uniform and complex forms that have an “organic and curved” nature that (historically) is considered to be beautiful. However the “chaining” of design to digital production then tests the initial design: The concept of the digital chain introduces the need to control design and process at both the individual stages, and also within the larger composite project.

Our work on digital ornament focused on three distinct issues:

- Relating traditionally intuitive skills of graphic and geometric design with the more constrained and explicit technological processes of parametric programming.
- Development of techniques of automated output using CNC manufacturing.
- Developing a project level “meta-view” on the methodological application of digital tools within a highly subjective project that is encouraging individualistic design.

The goal of these studies is to draw greater understanding between the subjective nature of design and the objective nature of digital tools; and to see how the ability of the computer to “control” processes can be put to creative use.

5.3.3. Ornament and technology

The craft of ornament is fundamentally and historically linked with the development of technology and design. The origin of art and design is founded in man’s discovery of tools and the ability to “mark” their surroundings. As this knowhow increased, these marking became more expressive, personal, and cultural. As techniques evolved, ornament eventually became regarded as a decorative art, but more importantly as a symbol of prosperity.[7]

As procedures for the working of materials evolved, so too did the *plastic and graphic arts*. Each culture had local knowledge of their materials and context, and evolved techniques for craftsmanship, art, and ornamentation became one of the bases for trade and exchange between cultures (friendly or otherwise!). As technology evolved, so too did the movement of man. Exchange and the propagation of technologies have had dramatic historical affect on design, production and architecture. The rise of the modernist or international style as a consequence of the industrial revolution is a direct representation of globalization due to technology. It is therefore not ironic that with this movement came the strongest calls for the rejection of ornament in design.

The lecture of Adolf Loos in 1908 “*Ornament and Crime*” is held responsible for the abolition of “traditional geometric ornament” in contemporary architecture.[8] Although Loos’s seminal essay seems to denounce ornament, the true condemnation was actually reserved for ornament applied without reference to context and culture. This thesis, and these practical investigations into ornament and technology, therefor seeks to reinvest in these issues of context and culture. By introducing the concept of adaptive design, through parametric programming, the concept is that a design responds to the input of its user or context to make itself contextually relevant.

---

[7] Trilling, J., (2001):p.14

[8] Tournikiotis, P.(2003),

5.3.4. Ornamental Justification

The design principles of ornamentation do exist in contemporary architecture; the use and highlighting of pattern, contrast of form, and differentiation of geometry are all still used to augment aesthetic complexity. These principles, through the use of technology and design techniques are now more often implemented at vastly different scales, or with different justifications, but the codification and optical results are similar to traditional embellishment.

> *"Mies and Corb found many of the work of technology and architecture of the 20thC. to have been beautiful. But it didn't fit their agenda to say they liked them because of their beauty, so they appealed to science, as the most prestigious force in society. So,… if you had an intemperate client and you wanted to persuade them that he roof should be one shape or another you would defend the design by employing science. We find the same types of argument going on to defend ecological architecture – the same emphasis that the reason that buildings look that way is because of ecological scientific programmes demand it. If you talk to Norman Foster about the Reichstag and why it looks the way it does, he will never discuss beauty, but he will defend it by discussing air circulation, water management, et cetera…"*[9]

5.3.5. Ornamental Evolution

One of the main methods for differentiated (and ornamented) design in contemporary architecture is the highlighting of materiality. In this we find the irony that Adolf Loos also employed the aesthetic characteristics of materials as his answer ornament. Loos responded to the loss of geometric ornament by engaging expressive patterning extracted from materials.

A frequent critique of contemporary architecture is that it is "boring", or that it lacks "character". By contrast historical, religious, and cultural architecture - embellished with ornamentation - express a clear character. The ornamentation of historic buildings reveals the relationship between advances in technology of that particular time and the evolution of that society and their culture. This architectural "storytelling" is a narrative that is visible, impressive, and appreciated by the public.

The resulting relationship between architects and the public has become sometimes confusing. Architects are expected to employ current engineering, materials, and technologies, in the creation of "beautiful" design, however the general public most often reveres the ornamented characteristics of historical architecture. "New and improved" are not always appreciated. The investigations into the digital design and production chain seek to address this issue.

The creative combination of these processes has potential for efficient diversity and uniqueness of design, while also compensating for the increasing cost and declining availability of skilled artisans.

The following projects (in teaching, research, and professional activities) demonstrate an ongoing experimentation with the digital chain. This work has been incorporated in real world projects, both in the revitalization historic buildings, and in the creation of new ornament applied in contemporary architecture.

5.3.6. Initial Ornament Investigations:

5.3.6.1. Texture Ornament.

The historic origins of ornament are that they were conceived and developed by craftsmen, from both their artistic expression, but from their abilities and understanding of their craft and tools. As such the first set of experimentations focused not on the intellectual design of ornament, but rather on the use of digital production tools, and understanding their relation to materiality and the forms created.

---

[9] Transcribed from podcast: deBotton, A. (2007) *"On The Aesthetics of Architecture"*

All methods of physical production leave indicative traces as to the way that they were made. In the traditional manual methods of making ornamentation, the tool traces are visible at different scales. These textures are evidence of the processes used and are the marks of the hand-workers. Dependant on the purpose of the ornament and the value of "appreciation" these marks are refined and reduced, or can also be amplified and exaggerated.[vii]

The first experiments of digitally produced ornament focused on these tool traces and the issue of understanding the relationships between the geometry, the fabrication machine parameters, and the resulting control of the surface textures.

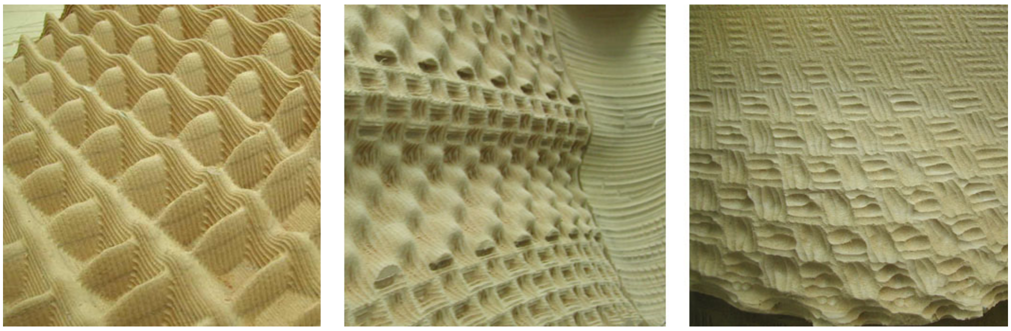


Fig. 5.3.6.1. Surface Texture: programmed texture ornament patterns that result from variation of CNC milling parameters.

An understanding of the manufacturing process was critical to the final aesthetic of the resulting texture. Because the textures were a "by-product" of the geometry and machining parameters – and not explicitly drawn or created by the designer – the learning process was specifically about determining the cause and effect of these parameters. The goal of the investigation was to understand and then control the actual design of the textural patterns, without explicitly defining the textures themselves.

5.3.6.2. Programmed Ornament

Despite the (contemporary western) association of ornament being a subjective creative expression of an artist or designer, a vast proportion of ornamentation is actually derived from explicit rule based methods of design. Islamic ornamentation is derived from rules of geometry and orders of mathematics. Calligraphy in many cultures and languages have explicit instructions for order and formation. The compositional layout of renaissance art and ornament were defined by theories of mathematic proportions and the golden section. And more recently contemporary styles of art-deco, art-nouveau, and even the simplified ornament of post-modernism had systems of geometry as their root and justification. These explicit design rules for ornament have an analogous correlation to programmed digital design.

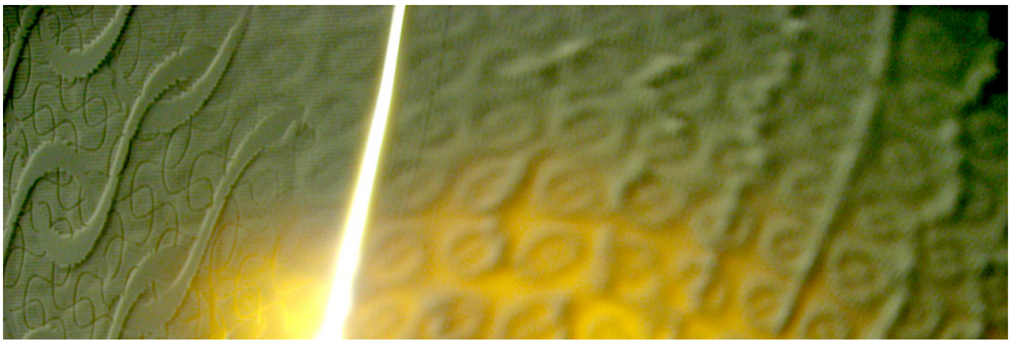


Fig. 5.3.6.2. Programmed ornament ceiling panels: programmed surface ornament patterns which adapt to varying surface topology, and where the ornamental patterns "blend" into each other.

By algorithmically defining a design, the resulting program allows for parametric variability in the resulting output. The incorporation of scripted variability makes a design "amorphous" until the context is prescribed and the input parameters also are made explicit. This method is conceptually similar to the catalogues and templates used for ornament in the middle ages. Craftsmen would use a template as an original model, but would alter the design in accordance with the local condition and application. In this way ornament had a continuity of style – a genus – but was variably defined for each individual situation, this is the root of the concept for *versioning*.

Investigations into *versioning* required student investigators to program ornament, which would adapt itself to variably defined surface geometries. The resulting ornamental panels are a combination of an original ornamental pattern, which mutates itself so as to adapt to the individual topology of its context. This investigation focused on issues of pattern, motif, and transformation, themes, which are all conceptually part of ornamentation theories.

5.3.6.3. Digital image interpretation script

Digital image interpretation as a method extracts the systemized organization of pixels in a digital image as digital data. This method allows designers to use complex but organized systems as an abstract data system to control complex topology (explained in DIGITAL TECHNOLOGY section-.-). Through the use of digital tools, and through the depiction of the data as an understandable but abstract representation, the user is able to better control multiple parameters at once.

For the following projects a photointerpretation program was written by Dr Kai Strehlke, and then further refined by this author. The small PERL script uses a module (Imagemajiks) to analyse and extract the pixel information from any image. In addition to the pixel values the program also creates a header block, which stores the dimensions, size, and image type (grey-scale, RGB; CMYK). This data is saved to a structured text file, which can be accessed by other scripts running in CAD programs.

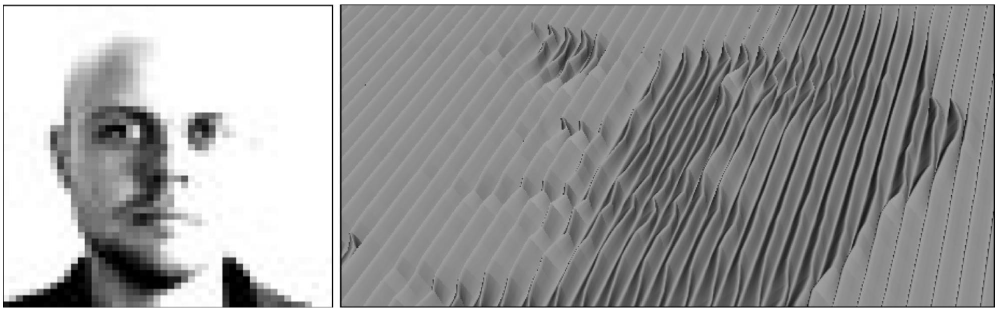


Fig. 5.3.6.3. Translation of image into an undulated NURBS topology (image: Strehlke, K.(2008))

This digital image derived method implies two distinct points: First, that the resulting ornament will be defined based on an image, including all shadows, imperfections, and any other artefacts captured in the image. Second, the base data is a normal digital image, and as such it can be manipulated easily for design purposes using image-editing software.

This advantage should be reiterated. The data is derived automatically from a digital image, so if the image is changed then the associated geometry also changes automatically. Thusly the value of the process is that a design can manipulate complex 3D digital geometries and topologies using sophisticated (but perhaps much more intuitive) image software (such as Photoshop).

Photo-interpretation software allows for a very interesting and intuitive “control” relationship between the designer and complex data sets. This effective and innovative method can create complex design results from data and rules, while still using a computationally efficient process. For the abstract and subjective process of ornament design this is a potentially elegant and optimized solution.

5.3.7. Eternit Ornament

"Eternit ornament" was a graduate elective course at the Chair for CAAD at the ETH Zurich, which took place in 2003, it was led by Christoph Schindler, Kai Strehlke, Andrea Gleiniger and the author of this work. The course goal was to investigate and develop new approaches to ornament using digital design and production technologies. Eternit AG was a sponsor for the course, and provided free material for the experimentation work and projects.

The work targeted two phases of digital intervention: design and fabrication. Design was digitally mediated by introducing digital concepts and methods including CAD tools, parametric design, and photo-based generative design. Production was then done using various digital fabrication machines: 3-axis milling, laser cutting, and waterjet cutting.

The biggest challenge in the course was the programming of the ornaments. Because of the steep learning curve of learning several new technologies; Maya (CAD), SurfCam (CAM), and the use of the CNC-controlled machines, most students found it difficult to also learn scripting and programming techniques. A workshop was given to teach basic programming, however most of the programming work actually was accomplished with significant assistance from the tutors of the course.

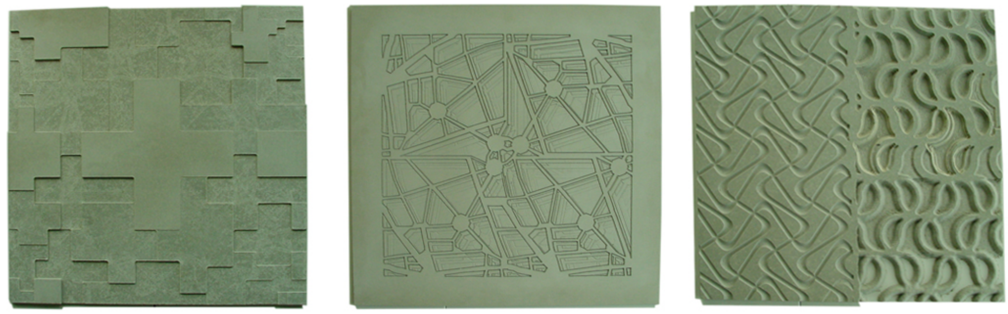


Fig. 5.3.7. Eternit Ornament test panels: CNC milled surface patterns exploring ornamentation within the depth of the panel using highly precise milling operations.

The projects demonstrated the potentials for ornament in a technological context of digital generation and custom manufacturing. The results of the course were the design products, but also the learning and experience of developing projects using a digital production chain.

5.3.8. The Rustizierer

On the occasion of the 200th birthday of Gottfried Semper, the Chair of CAAD at ETH was invited to participate in the exhibition "*Gottfried Semper, architecture and science, 1803-1875*" at the Museum fur̈ Gestaltung Zurich. The project "*Rustizierer*" was developed as a response to Gottfried Semper's rusticated and ornamented façades. This experimental project was conceived as an exhibition to present the potentials of digital tools in the reinterpretation of an architectural history and theory.

The Rustizierer uses photointerpretation of the original (manual) tool traces taken from high resolution digital photographs of the walls of Semper's ETH HauptGebäude building. The investigation developed different algorithmic methods to reinterpret the surfaces, not as a geometric reproduction, but rather as optical re-interpretation and perception.

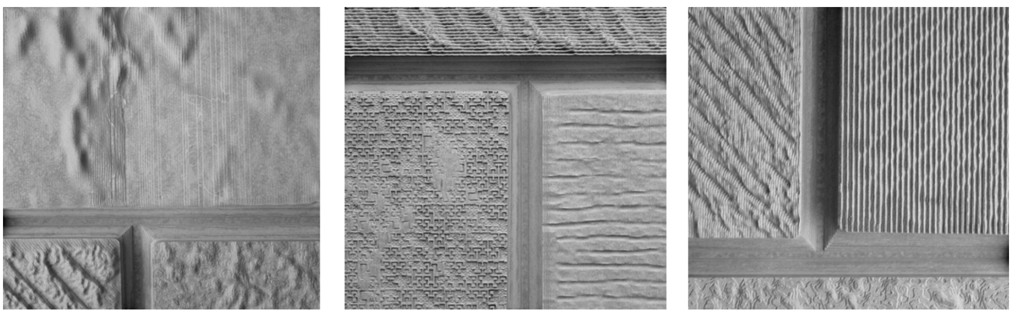
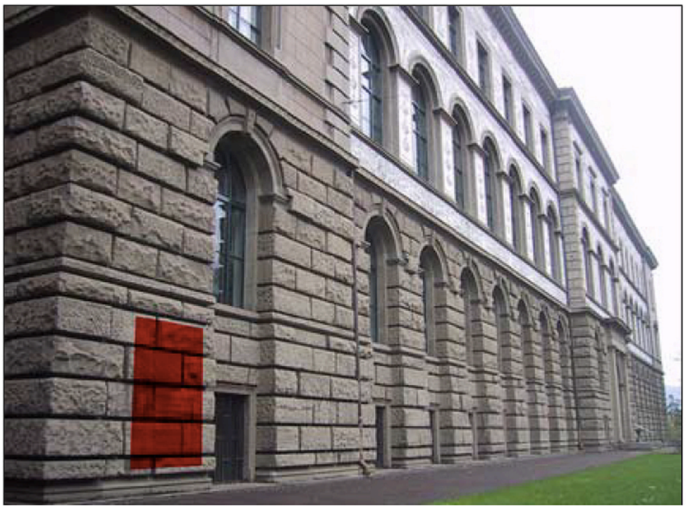


Fig. 5.3.8.a. Rustizierer - Semper Stones: Digital interpretation of rusticated stone carving,

Different algorithmic and fabricative techniques were used to experiment with the ability to play with the perception or interpretation of the surfaces at three different scales or distances: distant (optical perception), close (optical/intellectual perception), and contact (intellectual haptic perception). Algorithms and parametric CNC milling techniques were used to generate surface patterning which were designed to engage light and shadow effects. The resulting surfaces were designed to create different perceptive effects at the different distances.

The three experimental milled blocks were mounted in a scaled exhibition wall plate, which was imprinted with the photographic wall detail of the original source photograph. The resulting surfaces were aligned with the photograph, so as to allow for ease of comparison at the different "scales" of perception.



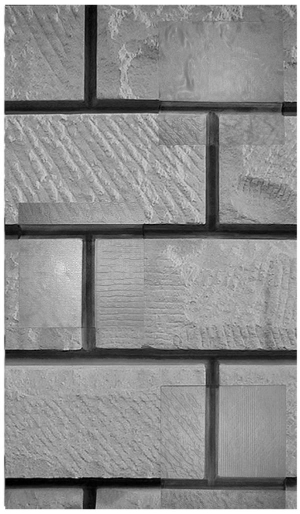


Fig. 5.3.8. b.) Rustizierer context: Wall section from ETHZ HauptGebäude. c.) Rustizierer Presentation: The semper stones mounted into the printed photomontage wall. (image: Strehlke, K.(2008))

The impression of visual continuity was strongest when we viewed from a few meters away. As the viewer approaches, the plates reveal the digital artificial traces that are created by the digital processing. In haptic examination, the blocks are clearly machine made and geometrically produced.

The intention of the experiment was to determine modes of digital development that address history and theory of construction, as well as human perception, while still acknowledging the role of technology in the project. The results demonstrate the capabilities for digital development and production, and how new technologies may be used to compliment existing historical architecture.

This project was developed in partnership with Dr Kai Strehlke, and is fully documented in the papers *"The Rustizierer: A dimensional translation of antiquity into technology"*[10], *and "The Redefinition of Ornament: Using Programming & CNC Manufacturing"*[11]. A detailed description of the programming methods and technological project development is provided in Dr Strehlke's doctoral thesis.[12]

5.3.9. Historical Building Facade

During the renovation of a historical building in central Zurich two highly ornamented exterior columns needed to be replaced. The historical designation of the building meant that the façade aesthetic was protected and replacement was subject to regulations and approval from the Kantonale Denkmalpflege.

---

[10] Loveridge and Strehlke, K. (2004).

[11] Loveridge, R. and Strehlke, K. (2005)

[12] Strehlke, K.(2008)

Three different competing methods were requested for evaluation. The first method cast the original façade and then made duplicate panels from fibre-reinforced concrete. The second method was a stylized version of the original plate composed from thin steel rods. The digital image interpretation process developed in the *Rustizierer* project was proposed as the third competing technique. After a first prototype round, the three designs were fitted to the facade for comparison.

The representatives of the Zurich Kantonale Denkmalpflege were originally sceptical of an overtly technological approach to making panels for a historically designated building; however once the mock-up panel was installed on the building their criticism turned to a positive response. In approving the proposal the inspector complimented the method as a "modernized re-interpretation, and not a direct imitation, of the façade"[viii]. For this (and other) reasons the *Rustizierer* based process was chosen for the project.[13]

Fig. 5.3.9. Historical Building Facade: Prototype competition: Direct composite plaster casting; Digital Ornament technique; Metal rod assemblage.

5.3.9.1. Context

The existing columns in the ground floor had a face dimension of 80 cm x 320 cm. These columns were to be replaced with thinner bearing structures, as such ornamented panels were conceived as cladding to maintain the original dimension.

The lead architects favoured metal or composites as the material for the panels so as to satisfy engineering requirements. Because the building already features metal details and ornaments, metal was chosen as the preferred material. The material characteristics of the chosen steel became one of the driving parameters in the project development.

5.3.9.2. Proposed process

The research team decided to experiment with metal and alloys. Digital fabrication techniques would be used to make parametrically controlled moulds into which steel would be cast.

The proposal for the project applied the previously developed digital photo-interpretation software, but developed new geometry algorithms to generate the surface topologies. The concept was to parametrically "undulate" a surface so as to create differential areas of shadow or surface brightness. The resulting surface geometry, when viewed from distance would give

[13] For a full overview of the competition details see Strehlke, K.(2008): p.78

the visual impression of a three-dimensional ornamented surface, based on the image data of the original ornamental columns.

This generated digital geometry would then be digitally fabricated using CNC milling equipment. This resulting piece would be used as a positive mould, from which a negative sand cast would be made. This sand cast would then be used for the actual casting of molten steel for the final panels.

5.3.9.3. Research goal

With the choice of casting stainless steel, it became clear that the characteristics of the material would determine most of geometry parameters for the rest of the process. The work in the project therefore became a research project to design a process model for the digital synthesis portion of the project, such that the resulting moulds were optimized for metal casting. As such, the main goals of the project were to develop a clear understanding of the production and material constraints, to have precise control over the geometric output, and to understand the optics, geometry, and materiality such as to be able to synthesize an image-surface that has an appropriate degree of visual and graphical resolution.

5.3.9.4. Data strategy

The digital design strategy uses the photo-interpretation software combined with generative scripts to create an "optical relief". The use of digital images as the initial data capture media avoids the need for complex (and expensive) 3D scanning technologies. Digital images are captured on location with a normal digital camera, with attention to minimize lens distortion and parallax. In addition basic physical measurements are also recorded, for correlation and adjustment. The digital images are then digitally rectified for perspective and angle to create high definition, grey-scale orthographic images (scale adjusted for measurements of the actual columns).

Once the columns images had been captured, the photo-interpretation software is used to convert the images into data-sets for testing in the generative geometric scripts. The development was a cyclical process of digital development, prototyping, visual and physical evaluation of the pieces, and then additional refinement.

5.3.9.5. Fabrication parameters

Initial milling tests were performed with "V cutters", tapered end-mills with a point end. The depth of a cutting path can be precisely and variably controlled when using a 3-axis router, as such the resulting line, and its corresponding width can also be precisely controlled to have a variable (but symmetrical) width. The resulting pattern resembles a "linear raster", a method for converting grey-scale images into a bitmap screen (black and white).

Upon discussions with the foundry specialists it became clear that pointed "V-cutters" would not allow for clean casting of the metal. Instead the foundry specialists provided four main geometric constraints related to casting with chromium steel alloy.

The first constraint was the slump angle for the casting sand. Casting sand is a mixture of silica foundry sand, bentonite clay, and carbon. The proportion and fine-ness of each ingredient is varied for the alloy being used, for the cooling process, and for the desired finishing quality. In this case, the 18Cr-2Mo alloy was used and as such the slump angle for the casting medium would be no smaller than 16 degrees.

The second sand cast constraint was the trough radius: the smallest "fillet" that the molten metal would completely fill. This radius was estimated by the foundry specialists to be 4mm.

The third geometric constraint of the sand casting process was the maximum depth of the troughs. This measure concerned the ability of the molten steel to fully fill the troughs and remain molten without partial cooling or trapping of any air. This was estimated at 12mm.

The final geometric constrain of the sand casting process was the minimum distance between two troughs. This determined the minimum localized strength of the deepest portions of the cast, as well as the potential resolution of the graphics. These four geometric constraints when diagrammed create a “optimum” profile for troughs in the casting medium. The second sets of prototypes were milled with an elliptical profiled grinding tool.

This grinding tool was chosen as it was a close approximation of the required trough profile, and was available as an “off the shelf” tool, however because this was a grinding tool, it was only possible to mill very soft Urethane foam-board (40kg/m3). To be able to rout MDF for the casting moulds this profile was then translated as a 2d section to commission the fabrication of a custom profiled end-mill for the project.

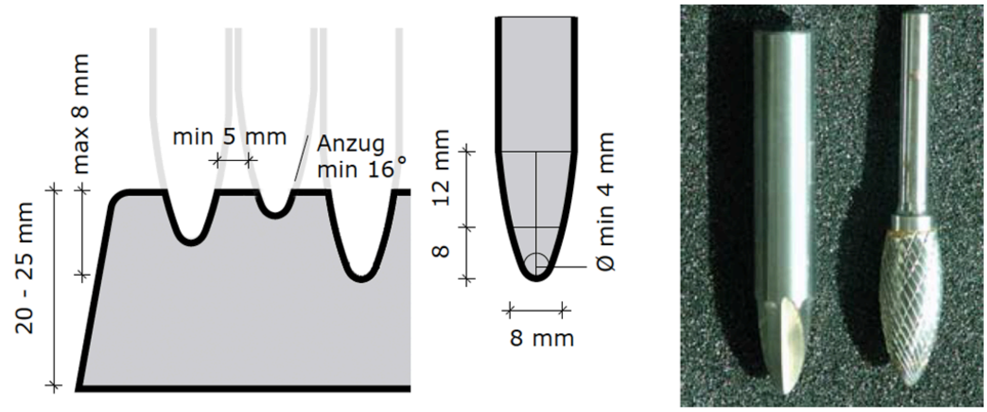


Fig. 5.3.9.5. Tooling strategy: Dimensions for tools based on sand casting parameters (ref: K.Strehlke)

5.3.9.6. Linear raster images

Combining the defined milling profile with vector splines as tool paths, reinforces the idea of linear raster-line images as the ornamental surface. This discovery allowed for a change of development strategy. The concept shifted from a design based on milling an undulating surface, to a strategy of engraving “parametrically controlled troughs” for casting.

By changing the process from milling to engraving there will be a loss of high detail visual resolution in the image, however there will be significant efficiencies from the simplification data, and optimization of fabrication process and manufacturing time. With the faster speeds also came fast “turn-around time” for design iterations, and resultantly an improved quality of the ornament resolution.

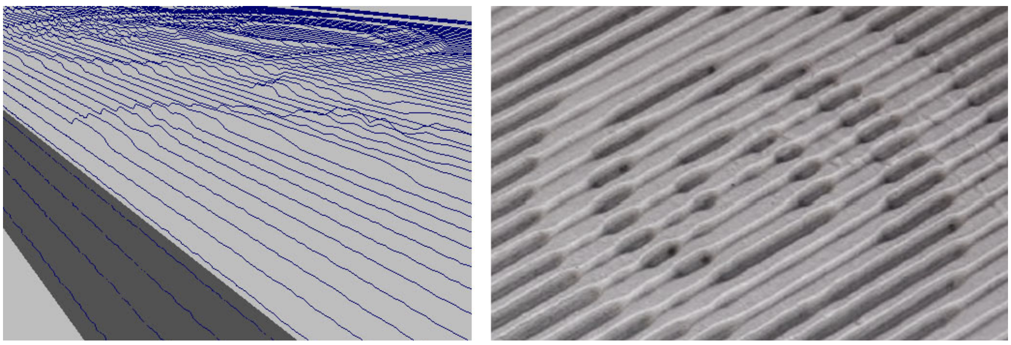


Fig. 5.3.9.6. Fabrication strategy: Using explicit spline geometry to define the milling paths.

5.3.9.7. Material efficiencies

The shift from surface milling to a vector milling strategy also allowed for relatively soft materials to be used for both the prototypes (80kg/m3 HDU – High density Urethane foam-board), and for the final pieces to be cast (MDF – medium density fibreboard). Because the interaction between milling and material was reduced lighter material could be used, and milling efficiency was improved.

With lighter material the router could be run a higher feed speeds (with less concern about wear on tools) and "turn-around time" for design iterations was improved. By cycling through the development process a number of times the overall processes and the interactions between parameters became clear. All of these optimizations allowed for additional testing, verification, and refinement of the design and process within the given time, and resultantly an improved quality of the ornament resolution. By the conclusion of the testing phase, twelve visual prototypes had been made.

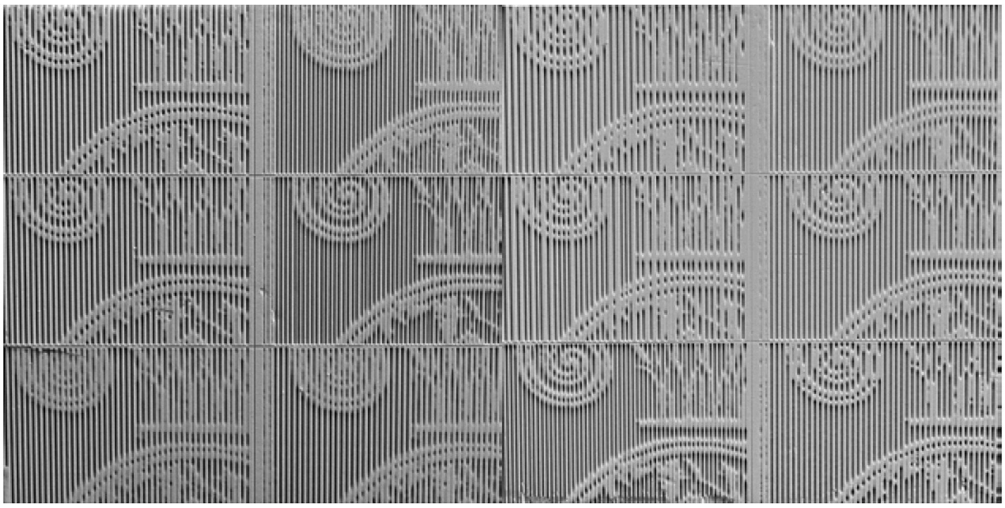


Fig. 5.3.9.7. Prototype: Fast prototype sections used for optical evaluation of ornamental effect.

5.3.9.8. Digital geometry development

The script for generating the digital geometry was written in MEL (Maya Embedded Language), and converted the image data arrays into linear spline vectors. The result was an array of splines oriented in the Y direction, whose control vertex points varied in Z height according to the associated pixel grey-scale values. The script was programmed with provision for parametric control of the spacing of vectors (determined by the fabrication constraints). Different variations were tested, but eventually it was determined that the spacing parameter was actually set due to the need for physical solidity of the mould.

5.3.9.9. Parametric variation prototypes

Fabrication of prototypes was made using a Precix 3-axis CNC router, and a variety of conical milling tools. The milled result has a surface depth of less than 8mm, however the visual result is fully three-dimensional. Initial tests were conducted digitally, but the main verification procedure was conducted physically by creating physical prototypes.

These initial fabricated prototypes revealed that computational processing of the images, resulting in straight "pure" halftone lines replicated the image accurately, however the resulting character was too "perfect" and synthetic for a "historical" façade. The geometrically perfect replication of the ornament did not visually integrate well with the existing historical ornament remaining on the rest of the façade. The addition of a randomized "wiggle" to the output from the generative script, reduced the visual rigidness" of the splines; enhancing the ornament and making it more appropriate to the historic appearance of the façade.

5.3.9.10. Image manipulation

The images for the process were required to be photographed at the same time of day and under the same lighting conditions, so as to ensure that the shadows were consistent across all of the ornament. The images of the ornament were further digitally manipulated so as to produce a uniform visual quality. Image editing software was used to "clean" the background, invert the main "icons" of the ornament for contrast, and to remove unnecessary small details that would "blur" the resulting surface impression. Because of the relatively low resolution of the production surface, it was determined that the digital images need not be high resolution, but rather a lower resolution (72 dpi was adequate) made the digital geometric calculation process more efficient, without any loss of quality.

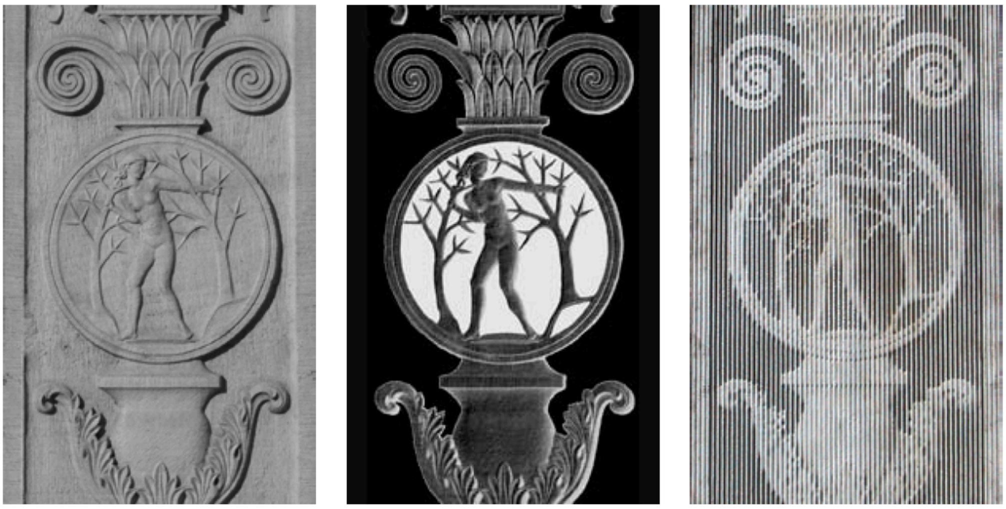


Fig. 5.3.9.10. Original, Digital image with manipulations, resulting milled surface. (Strehlke, K. (2008))

5.3.9.11. Positive to negative casting

The CNC mill was used to fabricate a series of plates, which were then used for creating moulds for castings in stainless steel. By using a process where the fabricated part is a "positive" (identical to the resulting cast part) there were two distinct advantages.

First, it meant that the panels could be assessed visually without additional processing (as the moulds being produced were identical to the final product). Given this, the milled panels could be mounted and viewed from multiple angles, distances, and under different lighting conditions ensuring that the visual effects translated as expected by the designers.

The second advantage was that the combination of a spline and an extrusion of the cutting profile, allowed for much simplified geometry (vectors) and much more efficient data processing. If a negative mould had been required (the opposite geometry) the generation of the surface would have been much more complex.

The technicians from the foundry provided knowledge about both the moulds and the casting process. In addition to the geometrical information for the tooling, they provided the thermal contraction coefficient of the metals after processing.

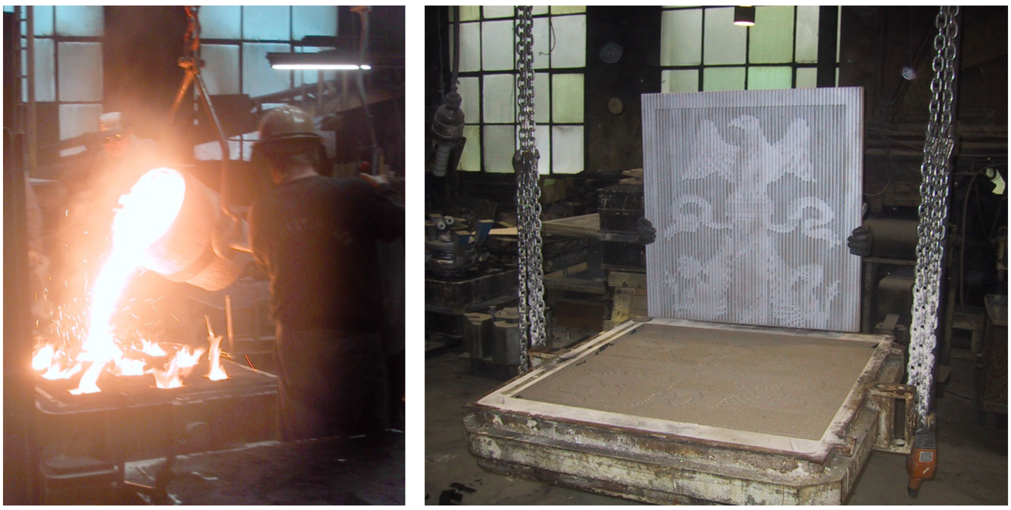


Fig. 5.3.9.11. Fabrication process: casting in chromium steel, sand cast panel (images: K. Strehlke)

After casting, a piece made with chromium steel has a coefficient of shrinkage of 2.7%. This parameter was incorporated into the generative design program, so that if a different alloy was eventually chosen the design could be easily adjusted. The geometry of the form needed to be adjustable to ensure that the vertical orientation of the grooves could withstand the thermal and fluid forces of casting a potential range of liquid metals. The resulting casting was successful and the design did not suffer from any damage to the mould.

5.3.9.12. Result

The resulting façade was considered a success on three levels. First the panels met all specifications for mechanical strength and function. Secondly, the panels were fully accepted by the Zurich Historical Board as a respectful re-interpretation of the original façade using new techniques and new materials. Finally the overall visual impression is conservative enough to not be noticed from distance, however when scrutinized the modern details of the process and material are apparent and clearly differentiated from the remaining façade.

The play of light and shadow in the "halftone screen" troughs creates an optical effect that makes the panels appear much more three-dimensional then they actually are. Although the troughs have a maximum depth of 12mm, the overall impression of the panels is congruent with the other columns where the ornament extends up to 50mm from the surface.

A final note relates to an unexpected "error" in the fabrication. In the casting process the steel that was used was contaminated by a small amount of ferrous iron. The iron was deposited on the surface of the panels, and after installation the panels all showed small "specks" of ferrous rusting. Although never intended, it was decided that the small spalling of rust enhanced the "historical" character of the columns, and it was chosen to not treat or remove these imperfections.

Fig. 5.3.9.12. Digitally ornamented façade panels installed on the historical building in Zürich.

5.3.9.13. Critical analysis

The skills associated with the creation of ornament have been in decline (at least in the western world) for the last century; new techniques for creating ornament may be required. The use of digital fabrication technology, which can be programmed to create ornament using rationalized processes, may be a possible and efficient alternative. With image derived generative geometry scripts it is possible to create ornament from existing examples.

In *The Language of Ornament*, James Trilling states "*ornament comes from ornament*". This newly derived process is somehow a modern interpretation of the historic ornament catalogues used by carpenters and stone carvers as a basis for their creations. Images and diagrams – alternate forms of abstract data - can be used as a starting point for digitally generated ornament. This process has a strong analogy to the contemporary concept of "versioning", the creation of a parametrically variable design from an original rhizome.

This project demonstrated the use of digital tools to control a complicated design process. The most influential parameters for production were actually derived from the final stage of the process, but for reasons of quality and optimization they were used to guide the front-end digital design and make is flexible and adaptable. If the materials or the production criteria were to change unexpectedly, the fact that the values are set up as parameters in a script mean that the new material constraints could be updated and parsed almost instantaneously through the digital scripts.

By using images as a basis for three-dimensional surface development, it is important to understand that the resulting surface is not a duplicate of the original geometry, but rather it is an interpretation of the "captured image", including shadows, artefacts, and imperfections. The use of images, as base data provides a clear working advantage, in that the seemingly complex output geometry is directly related to pixels; Images and pixels are intuitively manipulated in image editing software, thusly making the manipulation of complex topology equally intuitive.

This work is an exploration and reinterpretation of existing ornament using contemporary technologies. Although the processes used are fundamentally different from historical and traditional techniques of making ornament, the original depiction was not changed. By specifically not copying the work, but allowing it to be interpreted both graphically and materially, the resulting objects have a duality of character; they are on one hand certainly a respectful part of the architecture and the family of ornament visible on the rest of the building, but on the other hand they are something new and novel.

5.3.10. Schweizerisches Landesmuseum: Firedoors

In 2004, the architects Christ and Gantenbein were awarded the project for the renovation and expansion of the *Schweizerisches Landesmuseum* in Zurich. This multi-phase project will be an extensive reworking of the historical building, including all of the internal circulation. As the first phase of the project several "fire doors" needed to be installed for reasons of safety and security. Introducing new doors into a historically protected building poses a unique set of logistical, technical, and design problems.

Having been aware of the previously depicted projects, the architects Christ + Gantenbein approached Dr Kai Strehlke and the author to collaborate on the project[ix]. The brief for the collaboration was to develop a method for creating specifically designed 3D digitally ornamented surfaces from images, which should then be fabricated into solid oak doors.

This similarity to the previous research projects was immediately recognized, and was seen as an opportunity to iteratively refine the digital code and production methods. In this sense, the project was not technically innovative, however, for the purposes of this thesis, the project provided significant insight into the challenges of a significant "real world " project. The most valuable epistemological outcome was not a specific technological innovation, but rather it was insight into the issues of workflow efficiency.

From the onset it was clear that the project would face three main challenges: The first task was to convince the Zurich historical board of the merits of the design, that it was appropriate for such a historic building, so that they could approve the proposal. The second issue was to resolve the expectations of design and quality (given the final context of the Swiss National Museum) within a constrained budget. The third challenge was to use technology to enable flexibility within the process such that the influences from the first two issues could be controlled and accommodated, even as the project proceeded through different stages.

5.3.10.1. Constraints

Creating objects of high quality within the resources and expectations of the budget would be the main parameter of the project; as such this constraint was used to drive the project.

It became clear very early in the process that machining time would be the most expensive determinate for the project and that the expressiveness of the surface is typically inversely proportional to the speed of fabrication. As such the project would be defined by how optimally the door surfaces could be fabricated. The strategy for the development of the project became to manage the digital design and fabrication methodologies, such that every step optimized or facilitated production speed and quality.

5.3.10.2. Design

The physical materiality and characteristics of the project were predefined; The doors would be solid oak wood to correspond with the existing ornament of the museum, and the sizes and hardware were defined by fire regulations and the existing doorway openings.

The main difference to the HBF project was the intention that this *design artefact* should be a fully three-dimensional surface, and not a pictorial optical representation. The resulting design was to be immediately accessible to the viewer, both visually and tactilely. This meant that the surface would need a high level of sculptural resolution and would ultimately be perceived as an object, and not only as an image.

Fig. 5.3.10.2. Schweizerisch Landesmuseum: Existing ornament details.

The existing rooms of the *Landesmuseum* are characterized by ornamentation designed a century before, and themed on the plants and flowers of Switzerland. Christ + Gantenbein sought to reflect this ornamentation in the new doors, but with a modern re-interpretation. The concept emerged to use contemporary microscopy images of the Swiss plants as a “new” interpretation of the ornament. The micro-scale patterns seen in the modern scientific images would be used to generate a 3d textured “skin” for the new doors.

Microscopy images provided the base data to represent the complexity, harmony, patterns, repetition and variations found in nature. The goals of the software development were to develop methods of translating these aesthetic qualities into a topology for fabrication. This technological approach was developed in three ways:

- Adapt the existing code from previous projects.
- Refine the microscopy image to highlight the desired features.
- Develop a clear fabrication strategy, to provide feedback to the algorithmic design.

5.3.10.3. Digital Development

The geometry for the surface was derived using the same photo-interpretation software and generative geometry method as the previous projects.

The output from the generative script a set directly generated vector splines, which define the precise milling paths to be followed by the CNC machine. Parameters were defined to control the geometrical options (ex: degree of spline, number of interpolated points, and the relative depth of the 3d interpolation). Through setting these parameters and the "step-size" spacing of the lines, the texture and the definition of the design was controlled. By defining the output as milling paths, one process of CAM software interpretation is eliminated and this results in direct parametric control of the manufacturing time, …and therefor costs.

It is important to note that in the *HBF project,* because of the 2D nature of the panel and the use of a pointed tool to create a 3D *effect*, the geometry of the milling paths required no tool corrections. Tool offset corrections can induce geometric artefacts (such as loops and blebs). A second "filtering" script was developed[x] to optimize the CNC machines movements by eliminating "loops" or "kinks" in the fabrication code which cause a reduction in directional momentum of the machine. The benefits of this script were an improved cutting speed, while still maintaining the maximum "ornament per hour".[14]

Conceptually working backwards from the requirements for nice "clean" *G-code*, enabled an overall refinement to the design algorithms and process. By controlling the digital input, the generative script, and the fabrication parameters, it was possible to use digital programming to ensuring that the (costly) fabrication time was absolutely minimized. By finding efficiencies in production it was possible to achieve the sculptural and expressive qualities of the doors within the given constraints.

5.3.10.4. Image Development

After several tests and prototypes, the image of the "thistle" skin was deemed to be the most appropriate due to the high contrast and clear repetitive pattern within the image. Due to the complex (but intuitively manipulated) structure of image data (using tools such as Photoshop), the design processes could be controlled by members of the team who have little proficiency in digital design and no understanding of programming. The image was adjusted to (artificially) reinforce the clear topological features of the circular depressions.

The testing and refinements to the image and to the code were an iterative process, and the cycle went through multiple iterations of prototyping, evaluation, reflection and refinement.

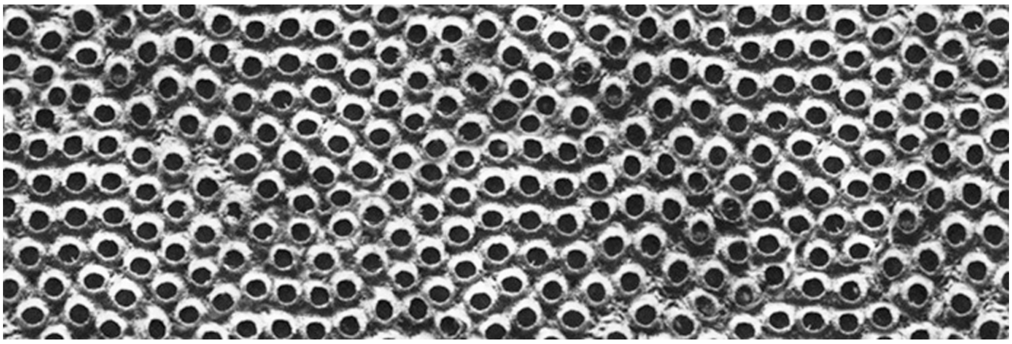


Fig. 5.3.10.4. Microscopy image of the thistle skin.

5.3.10.5. Fabrication Development

A three-axis router was chosen for fabrication; the ready availability of such machines in industry, as well as the relative simplicity of the driving code would ensure competitive costing for the fabrication. To further optimize production, the elimination of extraneous machining movements was investigated, and the first decision was that a single tool would be used to fabricate the entire surface. This would eliminate tool-changing time and minimize the need for multiple cutting paths.

Wood is a natural material with fibrous grain and irregular structure. European Oak has a very consistent and tight grain, but is a very hard wood that is prone to chipping. For the doors *Quercus robur* (Pedunculate Oak) was chosen for its relatively high density (720 kg per cubic meter) - which improves the fire resistance and burn time performance. The counter

---

[14] For a full detailed explanation of this process see: Strehlke, K. (2008): p.91.

point to this decision is that the material is tough and thusly has a high eroding effect on tools – "dulling" them quickly, raising concerns for the final surface quality due to chipping of the wood while routing.

A tool with enough shaft strength would be used for both rough cutting and surfacing and would allow for deeper cutting without concern of breakage. Because the surface was intended to have a rolling and articulated topology, a ball nose tool was the most flexible solution, however a larger radius ball nose also mean that the minimum concave carving radius would also increase, resulting in a decrease in sculpting resolution. Through prototype tests, the tool providing the best balance between size, strength, and sculptural resolution was determined to be a 12mm ball nose cutter.

5.3.10.6. Prototyping

The success of the project would be determined by a combination of the surface quality and the efficiency of the process. Although initial design decisions could be made from visualizations, because of the haptic and manufacturing time requirements of the project, prototyping tests were used to evaluate all final aspects of the process. The set of fabricated prototypes, made in lightweight, low-cost polyurethane foam, were evaluated subjectively for visual quality, haptic quality, and overall tactile characteristics (no sharp edges, no surface artefacts, and good resolution).

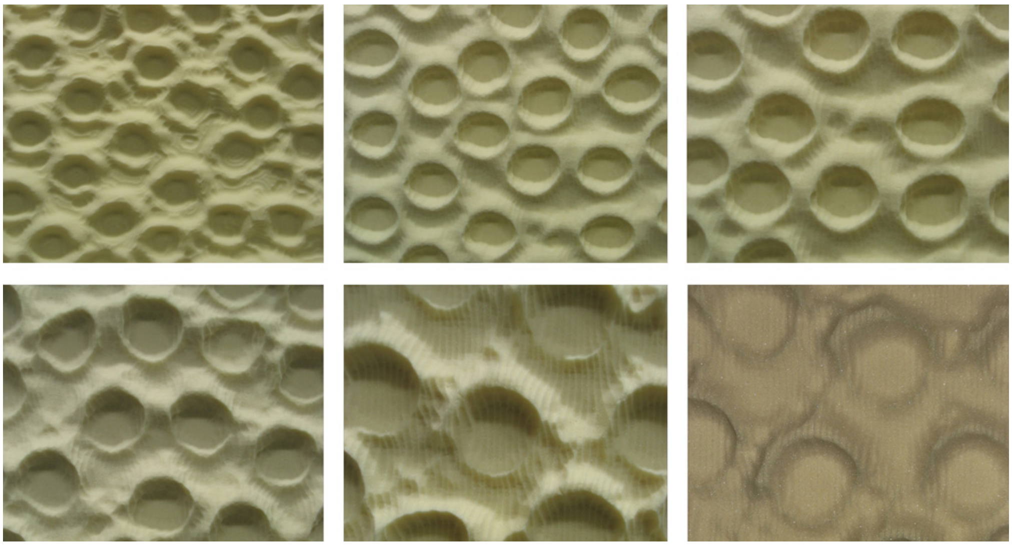


Fig. 5.3.10.6.a. Surface Prototypes analysis. Optical quality was the primary qualitative parameter.

The use of physical 1:1 prototypes also allowed for close cooperation and exchange between the architects, administration, members of the historic board, and the researchers. Although the extended members of the project team were, themselves not engaged in the digital development and fabrication work, the prototypes allowed for direct haptic assessment of the work and critical exchanges, ensuring that all parties were fully satisfied with the final result. Although the development of many physical prototypes is more expensive and time consuming, it was found to motivate the collaboration; levelling the discussion between technology and design, and giving the architects an immediate physical sense of the project, this in turn provided a basis for close mutual professional respect.

The final stage of prototyping was to work directly with the chosen fabrication contractor to create full scale, full material mock-ups of the door surfaces in the chosen solid oak. Full scale material prototypes were undertaken so as to determine the appropriate routing and feed speeds for the machining. Additionally the cutting path geometry was refined so that the minimal "step" overlap ensured proper chip evacuation and maximum sharpness of the tool over the course of the job. This phase of the project did also present some unforeseen and unique problems: Operators in this industry are typically used to manufacturing high precision parts for racing automobiles and for the aerospace industry. When presented with a project where precision and "fineness" of surface quality were secondary to the need for speed and budget consciousness, the operators were sceptical about the "rough" milling methods.

The milling method prescribed placed an unconventional (yet still completely safe) amount of stress on the routing tool and material. The resulting surface quality was "rough" but still well within the quality expectations of the project (measured by chips/m2). Because the team had already made 1:1 scale "proofs of concept" tests with our smaller production machines, the professional operators were eventually convinced of the production merits, and final refinements to the production parameters were made in cooperation with the technicians.

The resulting professional prototypes permitted a final evaluation of the materiality, colouring, and visual impressions of the pattern to be evaluated in the localized light conditions of the museum halls.

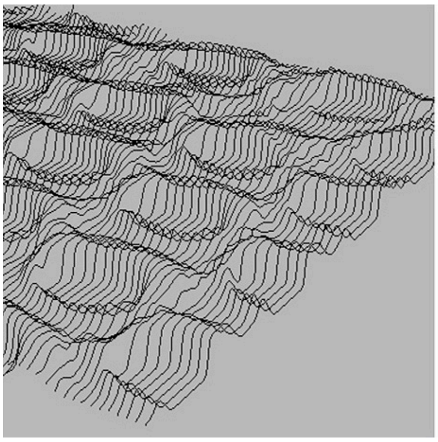


Fig. 5.3.10.6.b. Production results: Spline data for milling paths, resulting surface quality.

5.3.10.7. Control

Because of the historical nature of the building, the size and geometry of each of the eight door openings was unique. The parametric digital script accommodated this, but so as to ensure the continuity of the pattern across the closed doors, the doors were processed together as a pair. Additionally design details such as the corner rounding for the swing of the doors, and the installation holes for the door handle hardware (centred into a "divit" within the ornamental pattern) were included into the fabrication code.

The final production of the ornamental door surfaces was executed by the contractor; CNC Dynamix AG in Büron. The doors were milled in two operations on both sides as a final block. The doorplate sizes were a maximum of 3m x 1.5m, and each individual door weighted approximately one ton. After milling the doorplates were trimmed and finished with sockets for the mounting hardware, and finally the wood was sealed with urethane wood sealant.

Fig. 5.3.10.7. Ornamented Doors: Detail of surface – with installed custom opening hardware.

5.3.10.8. Critical analysis

The main task of the project was to develop a method of digital photo-interpretation of a surface textural pattern, and to effectively translate it into a fabricated 3D surface. The resulting method was fundamentally derived from the superposition of two different systems: Control and manipulation of complex input data, in this case the microscopy image of the thistle skin; and a generative algorithmic script. The resulting wooden surface can be seen to have a metaphoric analogy with the original organic thistle skin; as both are representative of the forces, materials, and tropism processes present in their creation.

This digital process chain defined all of the design requirements and explicit instructions that resulted in the ornamented surfaces of the doors. The design decisions and manufacturing parameters for this project were highly influenced by constraints of budget and resources, however, through the use of the digital tools these issues were controlled and the project was successfully completed.

The project underwent multiple iterations to develop the final code, input image, and optimal machining parameters, however it was the prototypes, which fostered strong collaboration, resulting in a clear technological solution for a well-conceived design. In the end, the clarity of the proposal and the resulting prototypes convinced the decision makers.

There are eight sets of doors installed on two levels of the museum, each set weighs over a ton, and the production was completed on time, and within budget. The doors were installed according to specification, and by all accounts the museum management is very pleased with the integration of new ornamented doors into the historically protected building.

Fig. 5.3.10.7. Ornamented Doors: installed at the Schweizerisch Landesmuseum.

5.3.11. Learning Center Hoarding

A hoarding is the protection barrier that surrounds a construction site. For many projects the hoarding has at least two main purposes. The first function is safety and security; the securing of the construction site, and the protection of persons near the site. Essentially the hoarding acts as a fence. The second purpose of the hoarding is to sign the construction site; to mark its existence, to advertise who are the parties responsible for the project, and often also as advertisement for the project (especially in commercial or residential projects).

The Rolex Learning Center was a significantly large and important construction site on the EPFL campus. With a high visibility location on campus, and a very large area, the hoarding for the construction site measured over one kilometre long along its perimeter.

The Learning Center Hoarding (LCH) project was proposed to the EPFL administration and to the team responsible for the construction of the Learning Center as "functional signage", which would both advertise the construction site and project, but would also demonstrate the capabilities of digital design and production at the EPFL.

This project proposed to create a series of large-scale perforated boards that would be incorporated into the construction hoarding at two strategic locations. The design for the signage pattern was a collaboration between lapa, Sanaa (the LC architects), and the EPFL team, and was produced using the large scale CNC milling machine that had been recently acquired by the lapa at that time.

There were three functional goals for the project. The first was to mark the hoarding and provide some visual signage for the construction site at a scale that could be seen from key points in the normal EPFL traffic. The second function was foster public interest by providing a perforated view through "windows" onto the construction site in prominent locations, allowing interested public to witness the construction. The final goal for the signage was to promote interest in digital architecture, by developing a high profile project – showing what is possible using EPFL technology and knowhow.

5.3.11.1. LCH Piccard

For practical reasons, the project was divided into two designs for two prominent locations. The first location would be located at the intersection of Avenue Piccard and Route des Noyettes. This is a main intersection visible from both the upper pedestrian concourse of the main EPFL building, as well as from the offices of the EPFL administration.

5.3.11.1.1. Design

The two main viewing locations (previously mentioned) are distant (+100m) to the hoarding. As a result the design was required to be large, bold and highly visible. For this reason the main design feature was simply the text: "EPFL-Rolex Learning Center". To demonstrate the possibility for variation and gradient in the design, this text was overlaid on an abstract background –modelled as a closed curtain (implying that the curtain would "open soon"). At the end of the curtain, located at the terminus of the pedestrian walkway, was a stylized plan of the Learning Center. The final design was refined in collaboration with the EPFL-LC team.

Fig. 5.3.11.1. Design of graphics for the Piccard – Hoarding: "The Learning Center Curtain"

5.3.11.1.2. Technique

The main motif for the LC is a rectangular plan, with several round-ish holes cut into it. This motif was directly adopted for the hoarding in the first phase. Using a variation of the previously used "image interpretation" code, the digital graphic design "images" were processed to create a data matrix of the pixel values.

A rhino-script was developed to interpret this pixel matrix data and convert the image data of the graphic design into a design, which could be cut into the hoarding panels. This data matrix had the explicit pixel data of location (X, Y) and the K value (black value) of each pixel. This data was transcribed parametrically to create a pattern of vector circles, thereby reflecting the circular hole motif of the building design.

The CAD circle matrix could be used as a direct cutting plan for 2D cutting using the large CNC milling machine. However before the design was finalized it would need to be optimized for the purposes of the site.

5.3.11.1.3. Optimization

The hoarding has three stated purposes. Signage, demonstration, but also to act as a window to the site. To ensure the safety and security of both the site and the passers-by, holes in any hoarding are regulated by the canton. The design was required to meet the canton regulations for size, durability, solidity, and also for holes. The holes could not be too large as to let a child's head pass through, and the holes also could not be such that their distribution would facilitate the climbing of the hoarding. After discussions with the cantonal inspector, a set of maximum and minimum values for hole size were agreed upon. These values became important parameters in the computational design.

Concurrently, the quality of the "image" of the design is dependant on the resolution of the hole matrix across the hoarding. A balance between hole size and spaced distribution was required, however the "resolution" of the holes would also determine the total number of holes to be cut, and this in turn would significantly affect overall fabrication time.

The final determination of resolution was determined by examining the resolution of the individual letters in the signage. It was determined that the maximum cell size should be no larger than 70mm so as to ensure full legibility of all of the letters in the text. This resolution would result in holes of a maximum size of 60mm, and a minimum separation between holes of 10mm, meeting all cantonal regulations for hoarding.

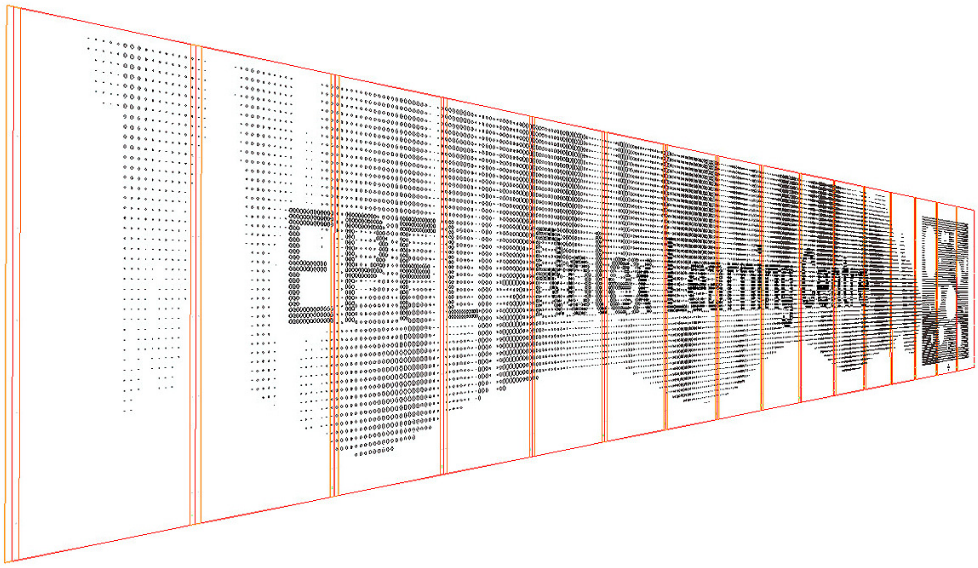


Fig. 5.3.11.1.3. Programmed Raster Hole Pattern – 16 milled panels at 1.5m wide: 24m x 3.2m.

At these measurements the resolution of each hoarding panel would be (at maximum) 22 holes x 48 holes, resulting in a maximum hole count of over 1000 holes per panel. For fabrication; given that each hole takes on average a little over 10 seconds to cut, and given that the transfer time between holes would likely be between 3 and 5 seconds, the cutting time for each panel would be approximately 4.5 hours. Additionally, the sheet placement and removal time between cutting jobs was on average 20 minutes. Meaning that the 16 panels that made of the Picard LCH took approximately 10 days of continuous 8 hour work sessions to fabricate.

From these calculations it can clearly be seen that a balance between resolution and process optimization was required. A finer resolution would have increased the production time significantly, whereas a lower resolution would have reduced the quality and legibility of the overall signage.

5.3.11.1.4. Fabrication

The material for the panels was white foil coated fir plywood. An initial small test panels had been fabricated as a 1:1 mock up, and had been installed outside of the lapa lab, so as to be exposed to the weather and elements. Due to the protective surface coating, and the relatively small size and vertical orientation of the cut holes, water penetration into the wood was deemed to be inconsequential. The small area of water permeation in the bottom horizontal edges of the cut holes suffered discoloration, but no significant material damage.

The panels were processed with RhinoCAM software for fabrication using the MAKA CNC milling machine at the EPFL. The panels were cut over the period of an extended week, and were cleaned and prepared for installation in the GC hall at the EPFL.

5.3.11.1.5. Installation

The installation of the panels was undertaken by Losigner SA; the construction company responsible for the construction site and the hoarding. This was undertaken by the construction company for reasons of legally liability for the hoarding.

Fig. 5.3.11.1.5. Installation on site at EPFL; strong sunlight shows effects through the hole pattern.

5.3.11.1.6. Result

The LCH Piccard project produced a large format signage with measurements of 24m long by 3.3m tall. The hoarding provided reasonable close view onto the north side of the construction, and a direct view onto the forming and construction of the main longitudinal archway of the Learning Center. The hoarding was in place for the duration of the two year construction period, and upon disassembly the material was still intact and showed no significant indications of water or weather damage.

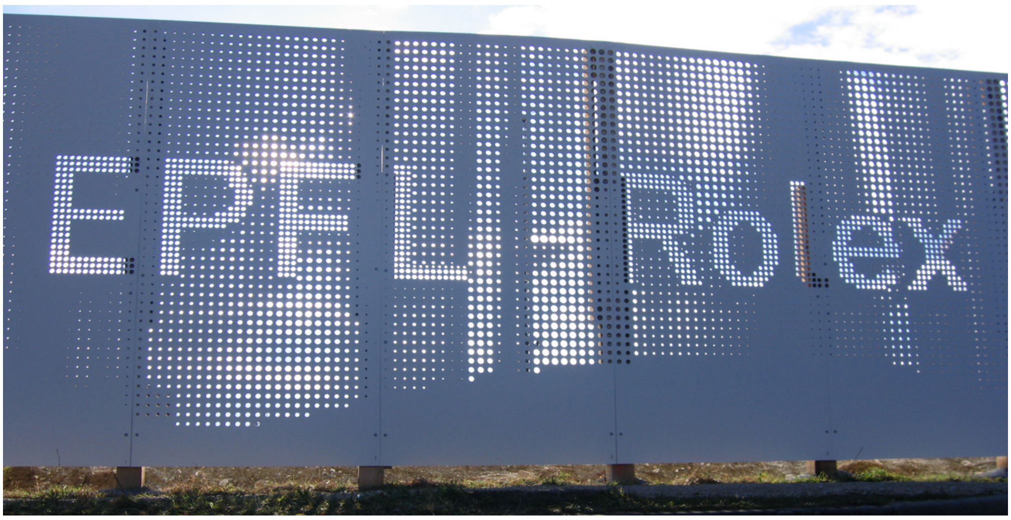


Fig. 5.3.11.1.6. Learning Center Hoarding – Piccard

5.3.11.2. LCH Esplanade

After the successful result of the LCH Piccard project, a second iteration and location was green-lit by the EPFL funding partners. The location for the second LCH project would be on the main axis of the Esplanade, immediately in front of the main construction office area, along the pathway of the entrance for all visitors to the site.

5.3.11.2.1. Design

The Esplanade location differed from Piccard in that there would be no view onto the actual construction site. The main purpose of the hoarding would be continuity of the fence signage. As there would be a greater emphasis on interesting perforations. The hoarding itself would be seen from both far away (across the open esplanade) and also from close (the sidewalk). From this, the resolution of the perforations needed to be addressed differently.

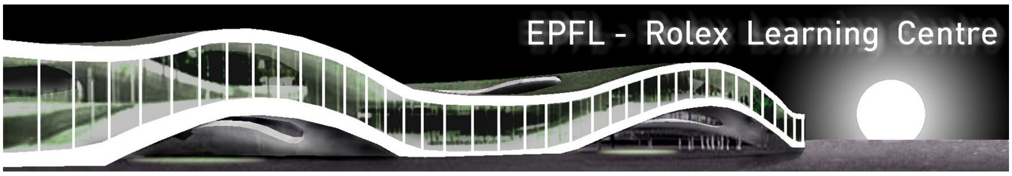


Fig. 5.3.11.2.1. Learning Center Hoarding – Esplanade – Design based on rendering of the project.

The graphics needed to be visually clear from afar, and highly engaging and clearly derived from technology when seen up close. In this respect the project had similarity to the goals of the “Rustizierer” project.[xi]

To accomplish these goals it was decided that the graphics would be derived from a rendered image of the Learning Center architecture, and that clearly defined “pixelization” techniques, akin to some of the algorithmic processes used in the Semper project would be investigated.

A perspectival rendered image (depicting the Esplanade facing edge of the building) was superimposed onto a gradient background completed with the “Rolex Learning Center” text. The image and text were graphically optimized so as to ensure that the quality of the text – with reduced size – would not dictate the resolution of the image.

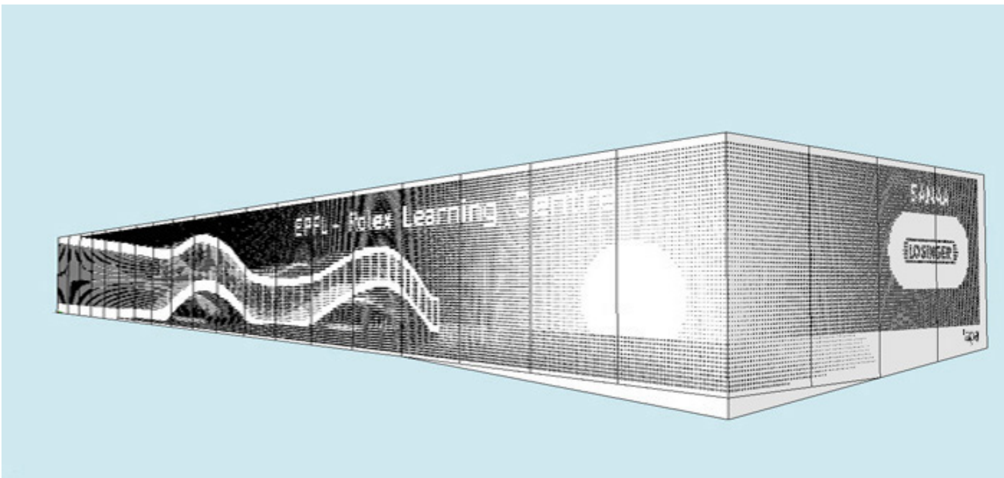


Fig. 5.3.11.2.2. Learning Center Hoarding – Esplanade – Design wraps the corner to site office.

5.3.11.2.2. Technique

For the LCH Esplanade project it was decided to work with four motifs, all four derived from the LC architecture. In addition to the round hole, used in the Piccard project, three other motifs in the form of the single wave, the double wave, and the enclosing spiral were also derived from the LC plans.

The original rendered image used for the graphic design was rendered in colour. As a result the image data contains additional available pixel information in the form of RGB values. However, for simplicity of programming and clearness of design, it was decided that the red and blue channels should be discarded leaving four values as the raw pixel data: X + Y (the pixel positions), K (black value), and G (the green value).

The addition of the green pixel value gave the ability to introduce a rotation to the motifs. Although a rotation would make no discernable difference for a round hole, for the three new motifs rotation animates their appearance across the surface.

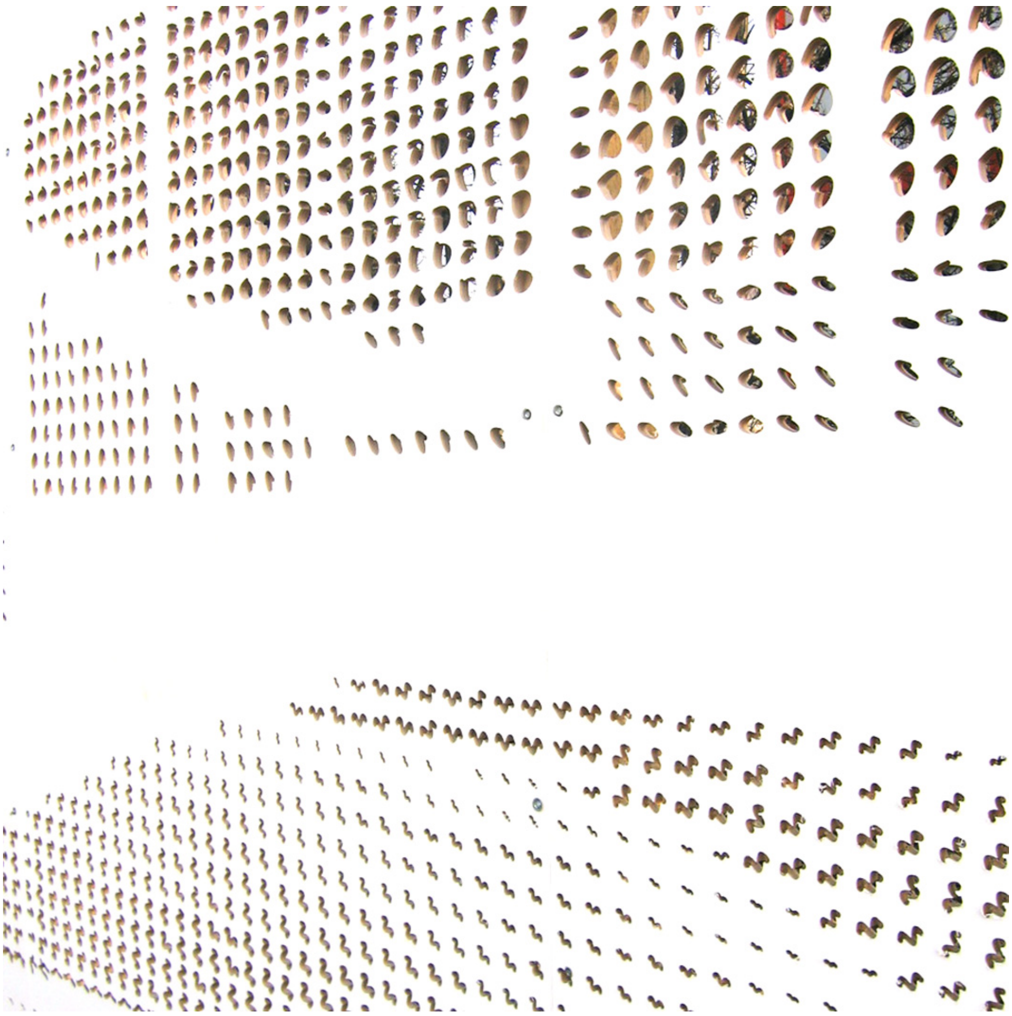


Fig. 5.3.11.2.3. Esplanade Hoarding – Motif based holes as extracted from the plans of the project: "round", "spiral", "single wave" and "double wave", used to differentiate foreground and background.

5.3.11.2.3. Optimization

As with the Piccard panels, the main issue of optimization was the balance between visual resolution and machining time. To improve machining time, an additional logical code was introduced into the rhino-script, which separated the vector motifs based on their K (blackness value) and placed them onto different layers. For higher K values, larger holes would be made, and as such larger tools could be used. The layers were categorized based on minimum and maximum hole sizes, allowing for organization of tool optimized for cutting; big tools for big holes, smaller finer tools for smaller holes.

Because bigger tools are much more resilient, they can be run at a faster feed rate through the material, thereby decreasing machining time. Smaller tools, are weaker and more likely to break under strain, so they could be processed for cutting at a slower speed. This organization allowed for efficiencies to trickle though the process, saving time, which allowed for higher resolutions to be used. The panels were processed with 50mm holes and 5mm spacing allowing for a panel resolution matrix of 25holes by 60 holes. The hole count of 1500 holes per panel is 50% increase from the previous iteration. Even though the resolution was increased the resulting fabrication time was reduced to less than 5hrs per panel, due to the increases in cutting speed. The production of the 24 panels for the LCH Esplanade was completed in 8 working days.

5.3.11.2.4. Result

The LCH Esplanade Hoarding is much more pictorial and complex than the hoarding installed at the Piccard site. The rotation of the motifs creates an animated effect across the surface, and makes the perforation pattern multifaceted; giving one impression from far (where the holes are not perceived), a different impression from the middle distance, where the holes are perceived but the image is still seen, and finally from close-by, where the motifs and their animation are the more dominantly perceived feature.

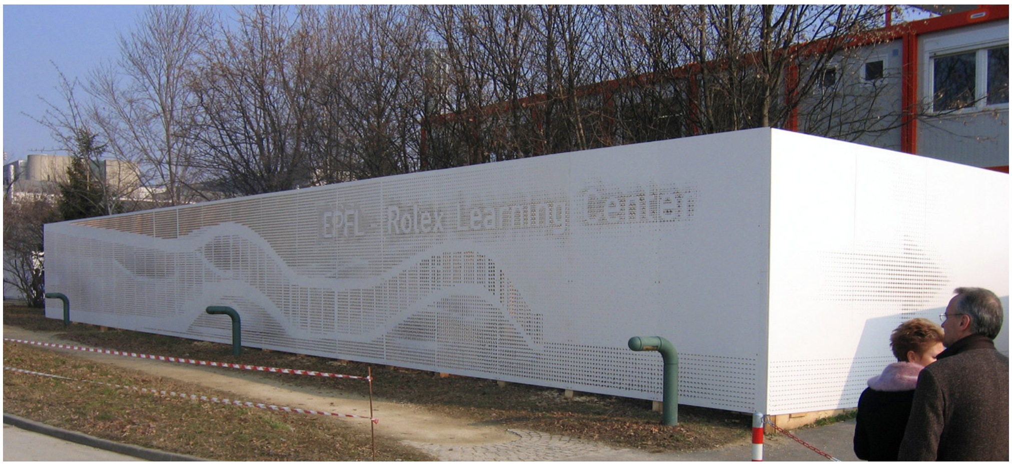


Fig. 5.3.11.2.1. Learning Center Hoarding Esplanade: Visual impression changes as viewer nears.

5.3.11.3. Critical Analysis

The Learning Center Hoarding project demonstrates the on-going potential for the control of data and the optimization of process using digital tools. The use of digital interpretation software for the decoding and subsequent translation of image data is a clear evolution of the processes used for previously depicted projects.

The ability to build upon the experiences of the previous projects and to find efficiencies and optimization methods were based both on the use of digital tools (parametric programming of resolutions, encoding of automatic layer categorization) as well as the intelligent set up of the fabrication and CNC controlled manufacturing.

The LCH projects were originally conceived to initiate the use and to provide experience in using the new large format CNC equipment at the EPFL. The projects were devised to test and reinforce skills associated with the fabrication of large individual designed pieces. However the most insight of the projects came from the development of the digital designs for the two projects.

The iterative development of the programming and digital methods used in both phases demonstrates the value of iterative evolution. Having a second phase to the project allowed for refinement and upgrading of the process, and allowed for investigation to look at additional parameters in the control of data. The second half of the project built on the epistemological experience of the first, and the resulting design demonstrates a higher order of managed complexity.

5.3.12. Control Conclusions

Throughout these projects two significant issues repeatedly needed to be understood when investigating the abilities of digital “control” with architectural design and production.

The first issue is "organization"; both the need for explicitness in the design methodology, but also the need for a clear method of managing large quantities of information, the structuring of data, and the ability to deal with instances that do not conform to the prescribed "system".

The second issue is the control of design itself. The ability to control a process is only possible when a notion of the desired outcome is known. As such in each of the projects and investigations, the resolution was done in two parts, the initial exploration, search and strategy methods, followed by the refinement of the problem from ill-structured, to an explicit method. This was primarily done using prototyping, and the full scale, full material mock-ups provided the final objective and subjective "control" for the process.[xii]

Once the designers were comfortable with these two concepts, their ability to work with the digital tools, and specifically their ability to manage data and control processes improved.

The intrinsic act of defining a "solution mechanisms (the algorithmic programming) makes clear the position of the computer as both a control and an "engine" within the architectural process. Explicit programming requires that the programmer (the designer) already has a clear idea of the desired end result. As such, the result in a generic solution case is already foreseen by the designer, and prescribed, and as such the *components* and their *relational architecture* of the solution method cannot produce something radically different from that which is foreseen.

Even when the further running of the script reveals aberrations, mutations, or unexpected results, the components and relations remain logically fixed, and as such the computer does not create radical innovation. As with any tool that augments man's capabilities, the concept and the direction must be a wilful intention of the user, the machine is used to augment this vector.

The "role" of the computer is therefor to clearly present the broadest possible data, such that it is appropriate for making decisions. When the magnitude of raw information is too much for the human brain, the computer is an effective tool for reducing and abstracting this information such that it can be effectively used at the human scale. For our purposes, this scale is the refinement of data such that it can be used for control over design processes, and specifically control of output.

The ability for computers to control information flow and to control output such that it can be used for production, is a great benefit to the ability to manage and control complexity in a design, but the computer itself is not able to produce radical methods, designs, or innovation.

5.4. Prediction

From our definition of the "information machine", the second stated capability is *prediction*.

Calculation is at its root an act of prediction. Using numbers (a symbolic model system) with the rules of mathematics (an intellectual rule set) allows the investigator to accurately interpret the potential outcome of specific mathematical conditions.

Different tools have been developed throughout history to assist with the process of calculation. The qipu, the abacus, and the modern calculator are all "systematic machines"; tools which allow the user to calculate abstracted situations. The advanced development of theoretical mathematics (and to a certain extent also philosophy), has permitted this form of production to evolve for different applications and disciplines.

Calculation combined with strict empirical positivism led to the "scientific method[xiii]", which is used to devise accurate conceptual models so as to allow further abstract prediction. The scientific method is the recognized objective proof for development of *repeatable and transparent experimentation*. When working in a design context, objective methods allow for the analysis, development, and understanding of context and behaviour, but alone objective methods do not (generally) lead to creative solutions.

5.4.1. Model Systems

Digital models are also *symbolic model systems*. If encoded with enough information and if the manipulation rules are explicit, a computer can be used to "calculate" a model. This combination of *control* of information with calculation results in the ability to simulate model behaviour under devised conditions. Once a model is verified to work reliably, it is possible to determine the probable effect of many different courses of action by changing parameters.

Simulation requires two models be developed: The *design model*, represents the design, and specifically its *architecture* (components and relationships); this is a static model, a representation of geometry. The second model is the *behaviour model*; an abstract model that encodes the key characteristics, rules of interactions, and dynamic processes that will be applied to the *design model*. Simulation is the act of applying the *behaviour model* onto the *design model*, and is calculated over time intervals (given that *behaviour* is a product of time).

Digital design has capacity beyond drawing and modelling. Because the digital medium itself is a computation platform, each model contains the base information required for prediction. Advances in computational power, sophistication of software, and ease of use has made digital modelling accessible for architects and designers. Now that modelling software includes the ability to model dynamic behaviour models, the act of design becomes enhanced with methods of advanced representations, which provide basis for better and faster design decisions.

5.4.2. Simulation

As a concept, prediction extends beyond the simple basis of simulation. Simulation develops a model, which reacts to specific input. Prediction relies on the input being analogous to the reality of a proposed situation and is also based on the interpretation and understanding of that model. Prediction is the ability to extrapolate this information from simulation, such that the model is consistent in other scenarios with different parameters.

In design and specifically in architecture there are many areas of practical simulation, each providing a different type of information feedback to the designer, which can then be used to inform design decisions.

Visualization in its many levels of precision is an obvious form of simulation. The simple ability to change views of a design in CAD programs (be they in axonometric, isometric, or more commonly perspective views) is one clear advantage of digital simulation. But taken to higher levels, visualization becomes rendering, and with the inclusion of applied digital representations of materials, lighting, shadows and visual effects, rendering becomes a "photo-quality" simulation. It is important to note that although this is clearly a computed depiction of how a design will appear, the evaluation of the quality of the view remains with the viewer and not within the software or system.

Other forms of simulation include simulation of dynamic human designed systems (such as traffic, train systems, or the operation of machines), the natural environmental processes (river erosion, weathering, annual foliage change in landscape design), or the simulation of complex systems (flocking behaviour, avalanche mechanics, or cloud dispersion). In all of these examples the simulation is passive, in that no interpretation of results is done by the computer. Interpretation is still in the realm of the user.

Advanced simulation, which includes evaluative programming, can reveal information which would otherwise be imperceptible to the designer or viewer. Including evaluative algorithms in simulation processes allows for advanced digital interpretation, which then enhances the abilities of the designer to predict complex outcome.

For the second stage of research in this thesis, the practical work investigates the use of digital tools which extend the capabilities beyond design and production, to include simulation.

5.4.3. FLOW

The FLOW project was conceived as a design experiment and coursexiv to investigating the issues of digital simulation and prediction. The project challenges the typical ideas of production media, and also to the way that designers perceive their ability to control the final design product.

Similar to the previous "ornament" investigations, this project introduces the design problem in a very constrained pedagogic environment, where the design goals were abstract and the main issues, although complex, were isolated from the larger environment. The working context should again be seen as an architectural testing ground where validation comes from knowledge and skill building.

The previously "ornament" projects focused on aesthetics with limited emphasis on design rules, the FLOW project as a corollary had the opposite emphasis. FLOW was an investigation into how artistic design can be achieved through the creative manipulation of rules and associative components within a design system. The project was set in a design environment where the functional rules are explicit and constraining, and the designers were required to learn how to create expressive results within this context.

5.4.3.1. Fluid dynamics

The investigations used "fluid dynamics" as a platform for creative experimentation and design. Fluid dynamics is the motion of fluid in a flowing system. Fluids flow in relation to forces of gravity and momentum. The flow patterns are governed by the geometry of their containing channel and any obstructions encountered, but they are also propagated by "self" turbulence within the fluid. The human understanding of such motion as a phenomenon is straightforward; but the actual interactions and rules of physics required to model and predict the actions of such systems are highly complex. The "self-affecting" interactions occur at the scale of molecules, then according to rules of fluid tension and viscosity, and finally at the scale of geometry. The cumulating effect of these interactions is a system of *organized complexity*, which is extremely computationally intensive to accurately predict.

The concept for choosing such a system for design experimentation is that the designer should have an intuitive idea of how the system will operate, heuristics about the media and its reactions, however as the desire for greater design control intensifies, the designer will need to employ more advanced digital tools to assist in the prediction of the system.

5.4.3.2. Flowscapes

The project was instigated as collaborative research with laboratories of hydrodynamics and fluids simulation, the laboratory of landscape architecture, and laboratory for digital design and production. It coincided with the Landscape Architecture studio of Prof Christophe Girot on the topic of "Waterscapes". The intention of the FLOW course was to develop a contemporary approach to dealing with fluid as a media for design.

The primary task presented to the participants was to use digital tools to design a "hydrodynamic water surface". Rather than the typical design goal of creating a static form that is then fabricated in solid material, this investigation challenged the designers to develop an understanding of a "dynamic system" such that they were able to "sculpt" the surface forms of moving water. To accomplish this the designers would need to develop an understanding of the different phenomena and forms that are common to hydrodynamics.

5.4.3.3. Analogies

The first phase of the investigation was to use analogies from other fluid systems to develop ideas and concepts for design. To do this different systems were investigated to identify features, and then to understand how these features are instigated and controlled. The investigations looked at different fluid systems and the activities that take place in these systems, such as flowing rivers and white-water kayaking, wind and aerodynamic testing in wind-tunnels, particle systems and traffic or crowd flow analysis, and other forms of laminar flow and turbulence.

Initial research and investigation into fluid-dynamics, the designers identified specific hydrodynamic features as the goals for their designs. (ex: standing waves, Karman vortex, hydraulic holes and pillows, eddies or eddie-lines, whirlpools…). The features were identified (from images, video, and from scientific documentation on hydrodynamics), and in each case the designer proposed to enact the feature in a creative configuration. As such, the task then became to identify the geometric configurations that act as “generators” for these features, and then using digital design, to model and refine the geometry such that under the correct flow conditions the feature is pronounced and easily created.

Different analogies were then adopted by the design teams. Examples of such features are:

- Eddies (and vortex edges)
- Whirlpools and Vortexes
- Pressure waves (pillows)
- Standing waves
- Kelvin–Helmholtz waves
- Von Karman vortex streets

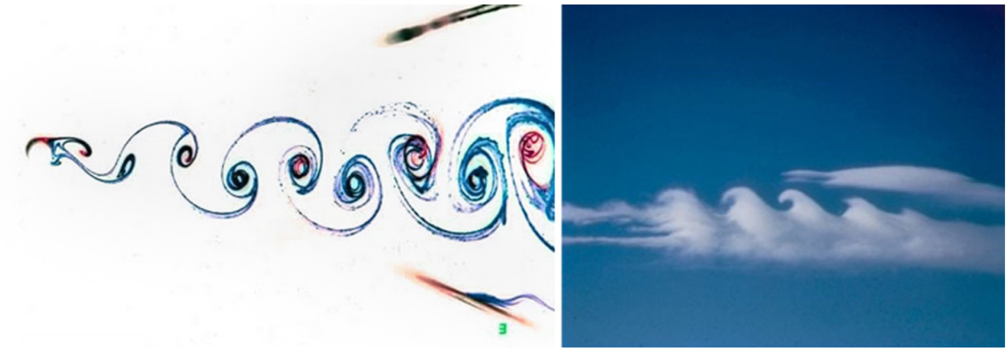


Fig.5.4.3.3. FLOW projects: Investigation analogues: a.) Von Karman Vortex Street; b.) Kelvin-Helmholtz breaking cloud waves (Photo: B. Martner).

Each of the fluid dynamic features was derived from large-scale real world phenomena, and the designers sought to re-create and control these archetypes by creating underlying channel geometries that would instigate the effect into a stream of flowing water. The design itself is therefor not the sculpted product of material design but is rather a moving geometric system, resulting from the interaction between the designed geometry of a “channel” (to be designed and fabricated using digital tools) and the hydrodynamic principles of water flow over this topology (to be tested and simulated using digital tools).

5.4.3.4. Hydrology and hydrodynamics as context for design

Hydrology is a field study that is now investigated with digital simulation (Computational Fluid Dynamics: CFD), but also still relies heavily on physical modelling and scaled experiments. The ability to develop digitally dynamic models, which accurately represent the complex interactions within viscous fluid flow rely on very advanced algorithmic relations, and require significant computation. For these reasons, the ETH Zürich, EPF Lausanne, and EMPA all still maintain fully active hydrodynamic testing facilities.

Course participants were given a basic introduction to the sciences and physics of hydrodynamics and were introduced to technologies used in the testing and predicting of hydrodynamic flow.[xv] For the purposes of the investigations it was important to understand how different technologies of simulation would affect the ability of the designers to create and “tune” their chosen features.

Parameters for the flow (quantity, viscosity, and speed) were given (and constant), so the main task for the designers was to learn how to model geometric surfaces, and then to learn how to test simulations of the surfaces so as to be able to (realistically) predict the resulting “water design”. Simulation would give the designer insight and feedback required for refinement of their design and the resulting fluid effects.

5.4.3.5. Modelling

Development of the geometry and testing of the surfaces was first undertaken using digital design and animation software: MAYA. This software was chosen for three main reasons:

First, MAYA is a NURBS (Non-Uniform Rational B-Splines) modelling software. NURBS and spine geometries were originally developed for the automotive and aerospace industries so as to provide mechanisms for defining "streamlined" geometries. Bezier curves and NURBS have specific characteristic parameters used to define "smoothness" and fluidity, making the geometry system appropriate for hydrodynamic design tasks.

The second reason for using MAYA is the advantage of its intuitive internal scripting language MEL (MAYA Embedded Language) which is straightforward and quick to learn.

The final and perhaps most important reason for choosing MAYA is that the program (and its animation engine) include tools for generating and simulating dynamic effects.

5.4.3.6. Simulation technologies

Three technologies were proposed for simulation and testing of the surfaces: The "digital effect simulation" software (MAYA), a CFD - Complex Fluid Dynamics software (Numeca CFview), and the testing of physical scale models in hydromechanics "channel" at the ETHZ. These three methods operated at vastly different levels of complexity, and with widely different requirements for resources, and with surprisingly different epistemological results.

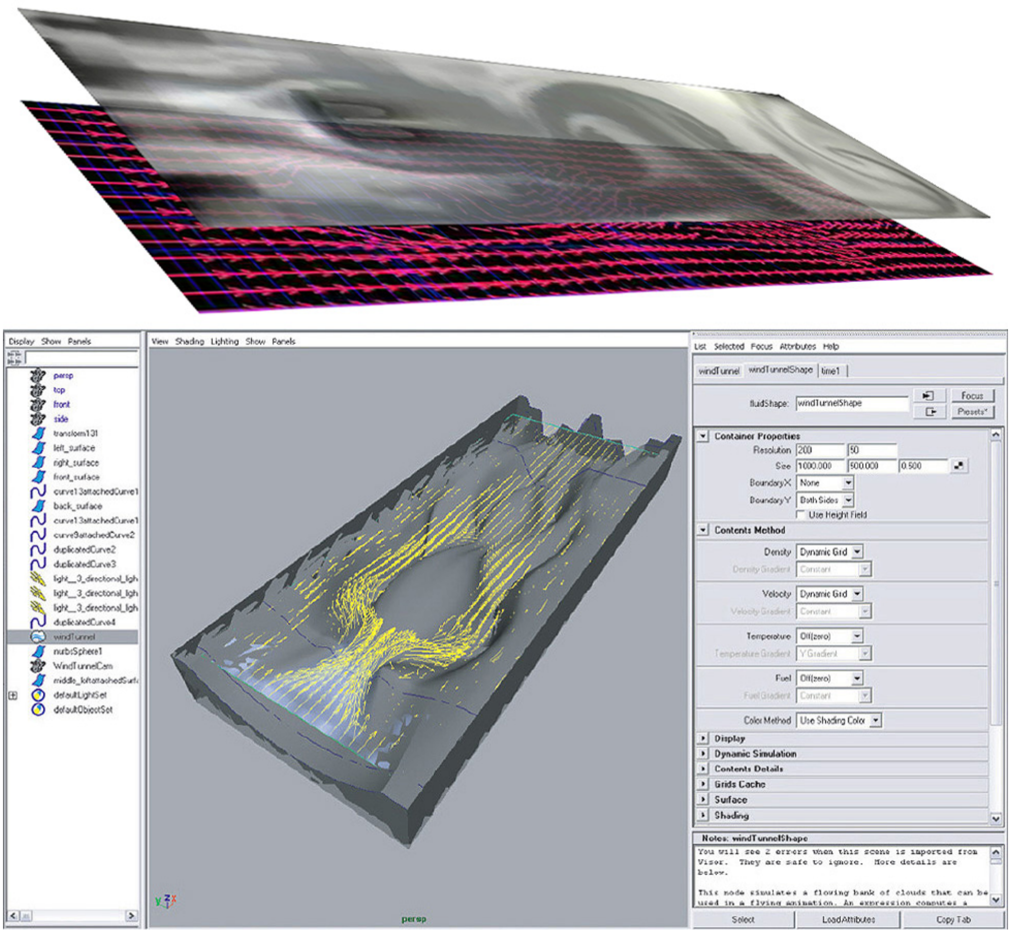


Fig.5.3.6. FLOW projects: MAYA as simulation platform: a.) Overlay of vector and graphic simulation; b.) Particle simulation and MAYA physics engine interface.

5.4.3.6.1. Dynamics Simulation

MAYA as a simulation platform allowed for fast, and (relatively) easy simulation of fluid effects in three different ways: particle effects, 2D- fluid effects, and 3D-fluid effects. The distinct advantage of using MAYA was the continuity of software from design into simulation. The problem with the software is that it is a GRAPHICAL simulator intended for film and animation. This issue is important to state: The simulation engine (the physics and rules used for dynamic modelling of processes in MAYA) is optimized for visual results, and not for true, real world, accuracy of physics. The simulation engine is modelled on real physics, and on the rules of hydro and fluid dynamics, but the engine is optimized for visual output. As such the accuracy and precision is sacrificed in exchange for ease of set-up and efficiency of computation.

The three methods of simulation in MAYA gave different levels of understanding (collisions, 2D, and full 3D), and the resulting computation times were propositional.

“Particle effects” is the lowest resolution of simulation, but provides good indication of how the fluid will behave at the fluid/air and fluid/solid boundaries. Particles interact with collisions but because there is no internal relation for viscosity the particles all act as independent agents and therefore the mass of particles does not well represent a fluid. Two-dimensional fluid effects were very useful for analytic representation of the fluid interactions in a section, but the simulation was of limited value for full three-dimensional designing. The 3D-fluid dynamics simulation was very computationally intensive, but produced the most representative results. The fundamental failure of this method however was seen at the fluid/air boundary, where it was difficult for the system to accurately represent waves or any form of splashing.

The main issues of note were that simulations were still relatively “coarse” for the level of design being undertaken. When the processes were scaled up to improve accuracy the simulation processing became highly computationally intensive (requiring much time) and therefore limited the ability for iterative design.

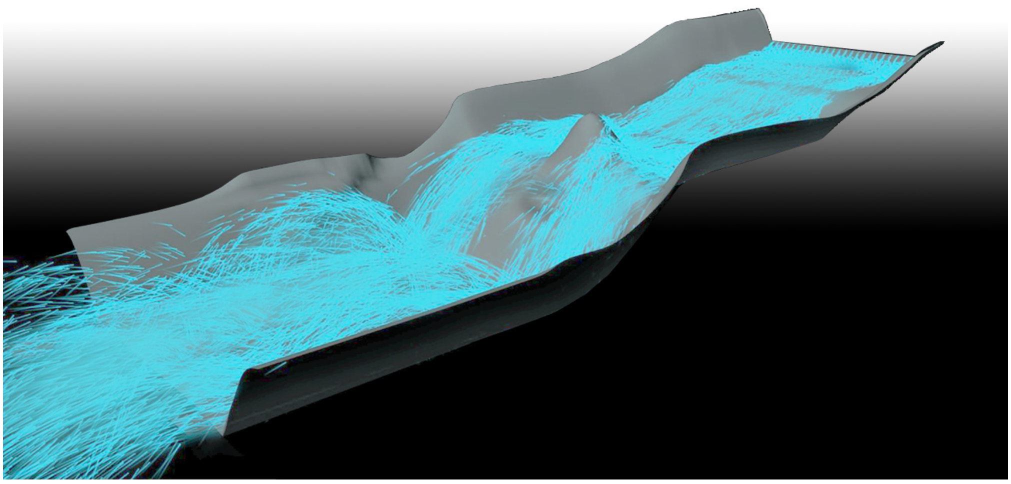


Fig.5.4.3.6.1. FLOW project: MAYA: Dynamic particle simulation. (author: J.Weiss)

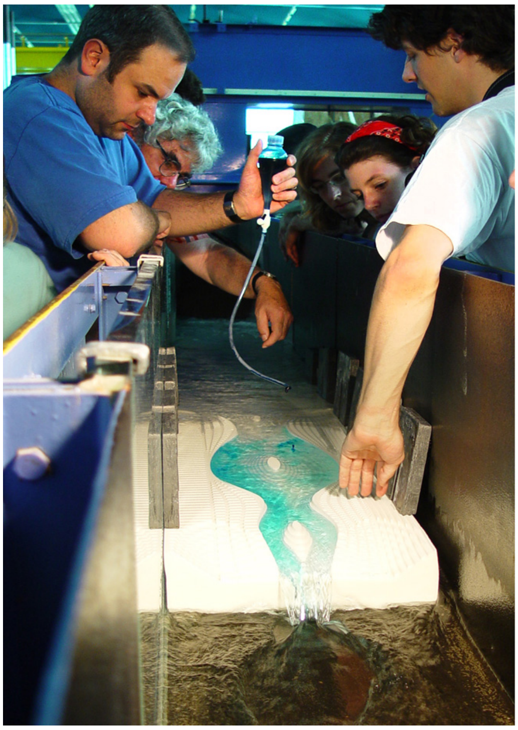
5.4.3.6.2. Computation Fluid Dynamics - CFview

CFview is professional-grade software designed specifically for advanced fluid and aerodynamics analysis, with specialization in turbine and laminar flow simulation. For this reason it was assumed that it would be an ideal package for this experiment. For practical and logistical reasons the software was not provided directly to the investigators; simulations were conducted by the technicians from the ETHZ chair of hydromechanics. The base geometry data was exported to CFview from Maya, and the set-up of the dynamic model was pre-set in the software. The resulting simulations were clearly of higher resolution, but also took significantly longer and required much more knowledge, understanding and care of setting parameters.

After one cycle of simulation it was decided by the investigators that, for the purposes of the project, and given the “less scientific” and “more abstract” nature of the project, the CFD software did not provide significantly more predictive insight.

5.4.3.6.3. Hydromechanics testing channel

To test the validity of the digital simulations, it was important to compare their result with a real scale test. The geometry of each design was fabricated in high density foam block, using CNC milling. These blocks were then installed in the ETHZ Hydromechanics testing channel and subjected to laminar directional flow of water at different rates. To be able to better "read" the fluid effects of testing, blue dye was injected into the water flow at key locations so as to be able to see the finer structures and turbulent details. The resulting effects were both



photographed and recorded on video for later comparison to the MAYA simulations.

Fig.5.3.6.3. FLOW projects: Experimentation in the Hydromechanics testing channel at ETHZ.

5.4.3.6.4. Results

The resulting comparison between the MAYA simulations and the video taken from the testing channel revealed that although the digital simulation lacked fine scale interactions (ex: splashing and small scale wave interaction) the main effect features could be reasonably predicted. Given this finding, it was possible to move forward and propose a design project using the MAYA simulation engine as a basis for predicting the fluid dynamics effects.

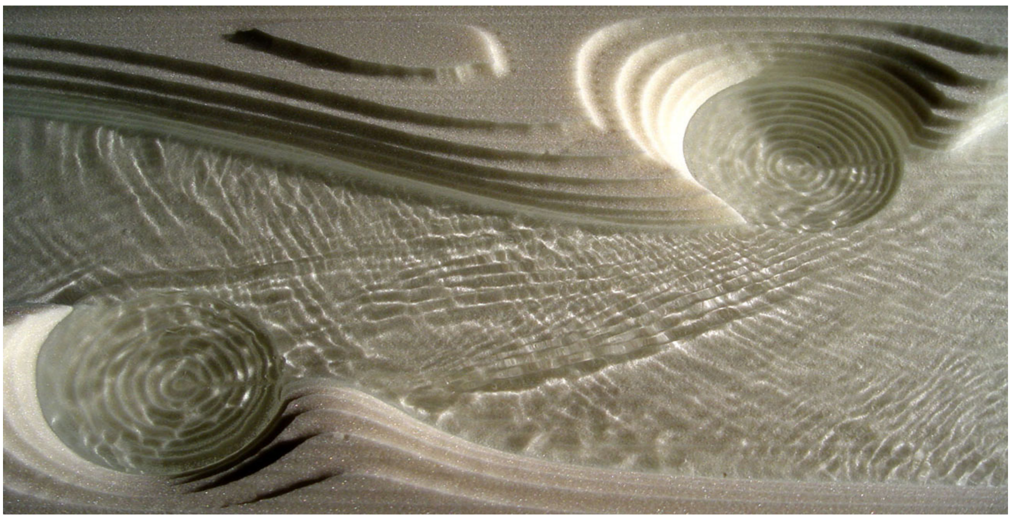


Fig.5.3.6.4. FLOW project: Detail of cross interference wave patterns (author: K. Zech).

5.4.4. FLOWchannel

To take this experimental investigation forward a design project was proposed to create a long fluid dynamics channel, demonstrating each of the "dynamic designs". Each investigator was responsible for one piece in a "chain" of formed blocks. The blocks, bonded together were provided with a water source at the head and a drain at the end, and the entire assembly was sloped so as to ensure constant flow momentum along the length.

This design proposal finds its roots in the development of fountains and water features from 16th and 17th C. Europe, and their historic role in the development of technology of the time. Specific historical references were taken from the "water chain" of the Villa Lante, the Villa d'Este, and the fountains of Versailles. At the time of each of these projects, innovations of technology were made to control the delivery, quantity and pressure of water to the fountains, such that the features" provided the designed results. Each of these projects, in their time, represent innovative engineering and design that was based on an understanding of fluid dynamics, and the ability to use (and perhaps even to predict) the effects from their designs.

The idea of FLOWchannel plays off of this historical and theoretical notion of water as an artistic media, and augments it to contemporary times through the employ of digital technologies.

Fig.5.4.4. a.) Original milled moulds for concrete casting; b.) the completed FLOWchannel.

5.4.4.1. Process

Each piece of this FLOWchannel is an experiment in hydrodynamics. Each investigator developed a digital topology with to replicate their specific hydrodynamic patterns developed in he previous experimentations, however in this iteration each piece had the additional constraint of having to "fit" with the previous and next piece in the channel. Digital simulation was used to verify the "water designs" would function, given the new connecting sections.

Several of the final models, those designs that had subtle or smaller scale "features", were further refined through additional physical testing in the hydrodynamics-testing channel. Upon conclusions of all of the simulations and experiments the designed topologies were integrated into a final arrangement to form the FLOWchannel.

The fabrication process for the FLOWchannel was to create each topology as an independent block, to be cast in solid (high fluidity composite) concrete. As such, the final topologies were milled as negative moulds, and then cast in concrete to create the set of final positive blocks.

5.4.4.1.1. FLOWchannel ETHZ

The FLOWchannel was mounted as a demonstration and piece and urban installation at the ETHZ Hoenggerberg campus for several weeks in the summer. The spectator could control the water supply and flow rate, and as such they could control the resulting dynamic effects on the individual surfaces. The feedback on the project was very positive in that it brought together in collaboration investigators from landscape architecture, hydromechanics, CAAD, and digital fabrication.

5.4.4.1.2. FLOWchannel Chur

After the success of the installation at the ETHZ, the FLOWchannel was invited to be included in an exhibition of landscape architecture related to master planning for the Rhine River at the Stadts Gallery in Chur. The FLOW Channel was installed outside of the gallery on the public pedestrian street (Vaserolgasse), partly as signage for the exhibition, and also a water-play exhibition for the street.

Fig.5.4.4.1. FLOWchannel Chur: The project was put on public exhibition as part of the Waterscapes show at the Stadtsgallerie Chur in the summer of 2005.

5.4.4.2. FLOWchannel Conclusions

The FLOW channel project provided insight into the use of digital simulation tools in design in a number of different ways:

The complex modelling and simulation software of CFview was clearly too detailed, complex, and unnecessarily precise for the needs of this "abstract design" project. The software may have the ability to map individual water particles and their progress through a flow pattern, but This was not required for the FLOW project. It was the larger "macro-scale" view of the system that was of importance to the designers.

The “visual” simulations used in MAYA were not empirical “physics based” interactions, and as such, still only abstract representations of the resulting dynamic systems. The quality of the simulations was directly relative to the complexity of the algorithms used to express the dynamic systems. However, for most of the design work, the requirements lay more on “good” simulation, balanced against efficient computation times, and the ability to iteratively refine the design. Once the practitioners learned how to do this in MAYA the process of iteration and prototyping became more efficient.

The physical testing of the models was clearly still the most detailed, and also pedagogically efficient method for developing design. The use of the testing channel provided immediacy of feedback to the practitioner, even if it lacked the ability to immediate make project level changes of digital re-design and re-testing. As a result the students became very proficient with making physical interventions in their test models (using knife and extra material). Although this meets with the needs of the design project, it does not support the notion of using the *digital chain*.

5.4.5. Critical analysis

When design problems are abstract or relatively simple, a professional can intellectually extrapolate predictions about their resolution. This mental process combines knowledge with experience and foresight, and is a skill that is extolled in professional practice. This ability to predict simple cases is an important component in “*reflection in action*”.

However, when the problem becomes complex, the permutation of variables can exceed the abilities of a professional to decipher to the problem. The use of predictive modelling and simulation gives the professional insight to enhance their own abilities, and to scale down the complexity of the problem such that they can *reflect* on it. The quality of a simulation also relies on the built-up experience and skill of professionals, in that their knowledge will be applied to making the simulation more applicable and efficient. The quality of modelling and the understanding of *behaviour* is analogous to the explicit encoding of professional knowledge; *reflection in action*, however, due to the inability of the practitioner to engage in the process – while it is happening - the simulation changes the methodology, so that only *reflection ON action* is possible in the actual design development.

The investigative work undertaken in the FLOW projects exposed the practitioners to the concepts of simulation and how it can be used in design. By creating a highly constrained *digital chain* (one that had a distinct focus on simulation and dimensional constraints), the individual projects could be amalgamated into a larger single design: The FLOWchannel.

The level of simulations used in the investigations were rudimentary, when compared to those used in CFD science analysis they were essentially “effects engines”; all the same, the results from such simulations were adequate to inform the designers as to the expected results of water surface. In highly abstract design, the intensity of the data only needs to match that level of abstraction; any more precision is unnecessary.

The intellectual understanding of an investigator improves with experience. As the tools and processes were used over the investigation period, the results of simulation improved, but more importantly and the “reading” of them improved.

The digital tools of simulation improve and continue to become more complex, robust, and adaptable, and with these evolutions the insight they provide will alter designers. Predictive modelling is both a tool for creative design solving, but also for professional advancement. Through digital simulation and evaluation, the paradigm for the professional has potential for radical change. When positioned in the current social and environmental context of needs for sustainability, energy efficiency, resource optimization, and social responsibility, the reason for the use of simulation and digital tools in architecture becomes much more pertinent.

5.5. Processing

The third ability of computation is the capacity for efficient *processing* combinations of complex instructions and high-level logic and mathematics. The ability to create iterative solution processes, and then to "run" them as an autonomous procedure is defined here as *processing*[xvi]. The differentiation of *processing*, compared with "software" or a script, is in the complexity of linked functions and the idea of a digital chain; a larger methods of linked processes. The ability to digitally link and automate such processes using programming is a fundamental change of methodology within architectural practice.

The following projects are the development of a single research concept that evolved with the experience, skills, tools, and access to technology. The entire chain of projects can be seen as an investigation into digital processing in architecture, which became increasingly complex, robust, and pragmatic as it evolved.

5.5.1. Folded Structure Systems

This investigation into the digital design of folded plate structures began with an overall investigation into structure systems.

The book "Structure Systems" by Prof Heinrich Engel is a milestone description of the different categories and types of structures used in architecture and engineering. The book, produced in the1967 is based on a multi-year research effort of Engle and his students at the University of Minnesota to document and model the structure systems. The chapters feature the six significant structure categories, and details each in terms of diagrams, detailed engineering, and the conceptual calculations of each system. Most interestingly for architects (and students) is that the work also features excellent drawn depictions of the systems, as well as images of student models for each structural system depicted, which focused on present multiple combinations and permutations of the different systems so as to show parametric variability.[xvii]

The combination of empirical depictions (structural algorithms), the demonstration of parametric variability, as well as the clear demonstration images, makes the book an encyclopaedia of structure. In reviewing this book, the idea for a digital design research and development project emerged; to replicate all of the systems as parametric digital models.

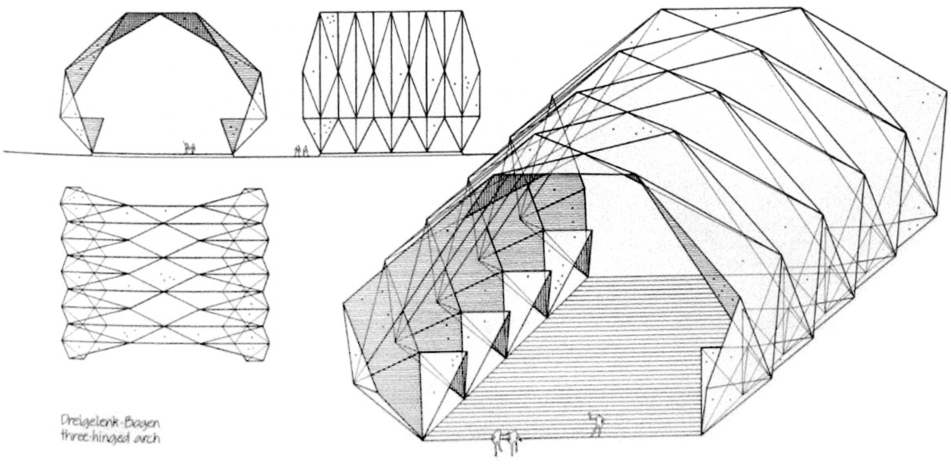


Fig.5.5.1. A page plate from "Tragsysteme - Structure Systems" H. Engel. Showing the types of diagrams for the "Surface Active" structure systems. (Engel, H. (1967):227).

5.5.1.1. Folded architecture

To test this concept, an initial test project to develop the "Surface-active" structure system (chapter 4[15]) was undertaken at the ETH Zürich.[xviii]

Surface-active structure systems are surfaces that have form, such that their surface geometry reinforces structural characteristics. If given specific geometric parameters, surfaces can perform load-bearing functions, either as flat planes (slab, wall, or beam), intersections (grids and waffle slabs), as sloped surfaces (composite slab-beam) or as curved elements (arches, vaults, domes). Within this set, this initial investigation would focus on folded surface structures, where edge folding structurally reinforces the sloping surfaces.

Structural continuity of a surface element over a fold provides resistance against compressive and shear stresses, and the added stiffness of a component can be used to resist torque. The geometry and dimensional proportions of the fold determines the overall resistance. The combination of geometry of the folded and surface continuity provides a composite stiffening of such surface-active structure systems.

> *"In surface active structures it is foremost the proper shape that redirects the acting forces and distributes them in small unit stresses evenly over the surface. The development of an efficient shape for the surface – from structural, utilitarian and aesthetic viewpoints – is creative act: art."*[16]

Folded structure systems and folded plate concepts have a long and well-established history of use in architecture. They are simultaneously the structure of a building and its envelope, forming the actual substance of the building and the criterion of its quality as a rational-efficient, and aesthetically significant form. The parameters of frequency, period, and amplitude of folding define the spatial character of both exterior and interior of the building, and are also determinants in the overall span, scale, and form.


Fig.5.5.1.1. Surface active folded structures: a.) United States Air Force Academy Cadet Chapel, (1962). Skidmore, Owings and Merrill (image: America, Library of Congress); Yokohama Port terminal (2002), interior. Foreign Office Architects (image: www.arcspace.com))

5.5.1.2. Surface Active Structure Systems

The first test structure system chosen for this work was folded plates, and specifically counter-folded linear plates. These structures are easily modelled and have relatively straightforward statics calculations. A second advantage for digital modelling was that the systems produce complex "looking" forms from a limited number of parameters. And finally the decision for this system was also predicated on the ability to produce scale model using flat sheet material (carton), and the availability of a laser cutter for digital production output.

The goal of the initial project was to develop a script that would allow for the parametric generation of "free-form" structures following the rules from *Structure Systems*, which could then be automatically unfolded and processed to flat sheet layout for laser cutting.

---

[15] Engel, H. (1967):p.212

[16] Engel, H. (1967) p.221

5.5.1.2.1. Geometry analysis

The geometry and organization of surface-active structure systems were analysed to determine the minimum required variables to create such structures:

- Frequency: the number of occurrences of a repeating event per unit sections/length.
- Amplitude: The static height of the counter-folding
- Phases: the number of primary inflections (hinge points) across a section (min =1; 0 would result in a folded slab, higher than 2 = a folded frame)

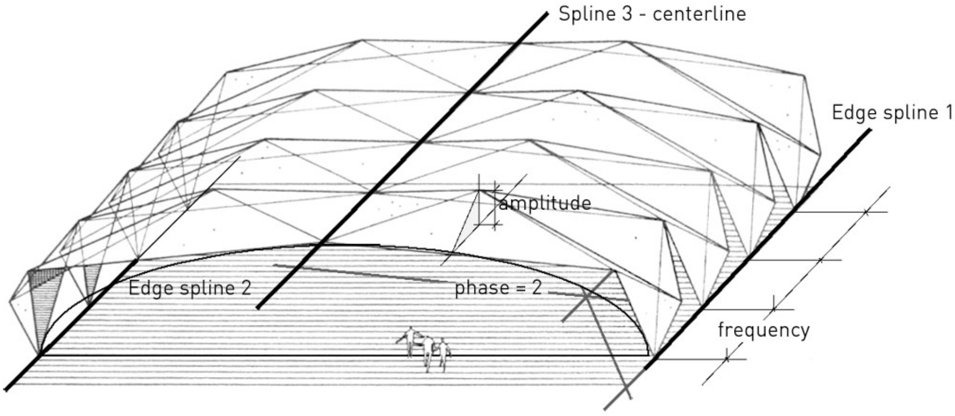


Fig.5.5.1.2.1. Analysis of surface-active folded structures to determine main parameters for digital parameterization: frequency, amplitude, and phase. The main geometry required are three guide splines: 2 edge splines, 1 centre spline.

The overall shape of such linear structure system is that of a vault (and extruded arch). The vault geometry for the structure was therefor defined by three (conceptually parallel, but parallelism is not required) splines: the two “outer” splines represented the two edges of the structure, and the centre spline represented the crown line of the vault. The resulting structure was based the “lofted” surface between these three lines. These three spines were not constrained in any way, meaning that they could be 3D, non parallel, and highly complex; however the best, (most understandable, and most rational) results came when they were moderately parallel and defined a clear vault geometry.

5.5.1.2.2. Scripting

For the project MAYA was used as the digital CAD platform for the development of the digital models, and MEL (Maya Embedded Language) was used for the scripting of the generative code. The first iteration of the code was designed to produce a simple triangular arch.

The code functioned by first rebuilding each spline as a (degree:1) polyline with the number of nodes defined by the given parameter of *frequency*. Each of these individual line segments was then subdivided into 2, and the node-points shifted in the normal direction by half of the *amplitude*; The centre polyline nodes were shifted in the +/- Z direction, so as to achieve a structural static height. The result was that each of the segments along the length of the edges and centre were converted into a “V” arrangement. Through a looping iteration routine (based on numerical ordering); the segments from the edge lines were lofted to the node of the centre line, and the centre segments were reciprocally lofted to the corresponding node points of the “edge lines”, creating a system of triangular polygons.

This script was later augmented to include a variable for *phase* (our nomenclature[xix]). This parameter subdivided the (perpendicular) sectional geometry (the arch section of the vault) through the addition of “structural hinge” points that allowed for undulation (wave geometry) in the sectional direction, as well as along the length. Including the “phase” parameter allowed for complex counter-folding, and the creation of “origami” like structures.

The resulting script allowed for digital generation of any liner folded plate system geometry, from three parameters, and three drawn splines. Although the best results emerged when the three splines were roughly parallel, there was no actual limitation, and the script would calculate the results without any bias to constructability, or any other constraint of reality. This resulted in some very "abstract" results.

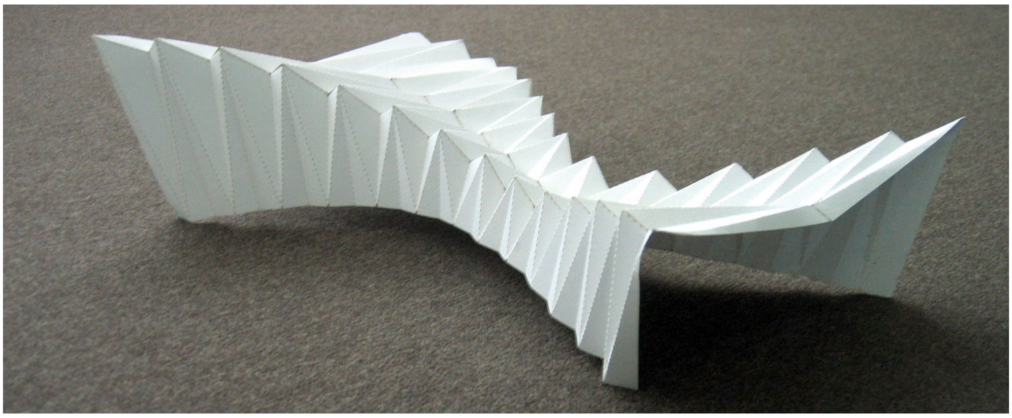


Fig.5.5.1.2.2. Paper model from algorithmic program: Origami" structure is computationally unfolded into four flat (x-fold strip) template pieces, laser cut, pre-folded, and glue assembled.

5.5.1.2.3. Output

The code was designed to produce a 3D digital geometry model, but additionally it was designed to then "flatten" the geometry into flat-cut foldable pieces, which could be cut (and scored for folding) with the laser cutter.

Due to the counter-folding geometry, the structure could be easily divided into longitudinal "strips", with the number of strips based on the *phase* of the vault. Each strip would be a series of diagonal counter folds. Using an additional script the structure was divided into the "strips" and each strip was unfolded ("*unwrapUVW*") to create a flattened cutting pattern, to be cut with the laser). The script was also programmed to include an option for the creation of "tabs" for ease of assembly when using paper or carton.

The resulting vector patterns were coded with (black) "doted lines" for folding, and solid lines for cutting. In this way the file could be exported directly to the laser-cutting machine without need for further need for manual adjustment of laser parameters[xx].

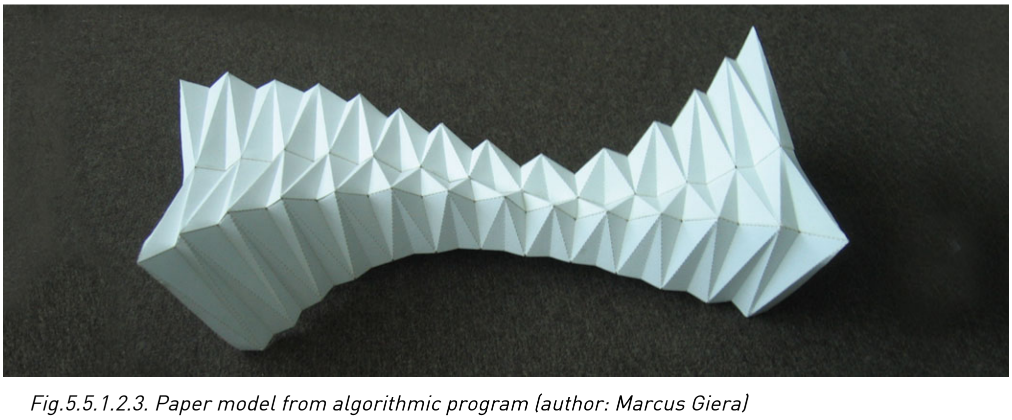


Fig.5.5.1.2.3. Paper model from algorithmic program (author: Marcus Giera)

5.5.1.2.4. Postscript + closure

The intention to continue this project with the development of more sophisticated models and the digital parametric definitions of other structural systems, from the chapters of *Structure Systems* was never achieved. This was due to the authors' departure from the ETH Zürich, to move to the lapa and the EPFL. The concept of developing these models further as an academic exercise is still valid, and would be beneficial as both a pedagogic experiment, and as skill building exercise. This may be undertaken in the future.

5.5.2. Alucobond

The interest in folded plate structures was revitalized several years later at the EPFL due to two sequential collaborations.

The first was a collaboration with the Alcan Innovation Cell, and their assistance in securing material sponsorship from Alcan Composites Switzerland, for investigation work with the material Alucobond (a composite of aluminium sheets bonded to a core of polyethylene).

The second collaboration was with Dr Hani Buri of the EPFL iBois Laboratory, in conducting initial experiments on folding of Alucobond as so as to give it structural form. The doctoral research of Dr Buri was conducted on the design, development, and structural analysis of "Origami, Folded Plate Structures" with specific focus on the use of timber plate construction systems.[17]

The investigations resulted in the development of methods to first machine the flat sheet material (using a CNC routing and cutting) and then fold and counter-fold Alucobond, such that it could be used structurally in folded plate structures. Due to the composite sandwich section of the material it was possible to control the angle and stiffness of the folds by varying the depth and profile of the cuts made. The initial experiments provided a basic methodology of processing that formed the basis for several further design-focused investigations. The results of this initial investigation are documented in Chapter 10 of Dr Buri's doctoral thesis[18].

Fig. 5.5.2. Initial folding tests of Alucobond: Collaboration with Dr Hani Buri; iBois, EPFL. (image: F. Perrin)

5.5.2.1. Initial testing

To determine design potential of a material and its connection to production methods, *fabrication test* were undertaken. These tests are both empirical and subjective evaluations of how the material performs under the specific conditions and stresses of machining. These tests are fast and simple process investigations to figure out what is possible, but also to find out where the material will fail.

From these initial investigations the decision to use folding as a primary technique for design development was reinforced. The main issues of consideration was the ability to control deformation and tolerances of form, the visual quality of the material after processing, and optimization of variability of form in relation to the requirements of design and processing time. Simply stated; using folding as a design system had the same advantages as an *emergent* system: several simple rules created forms of high complexity.

---

[17] Buri, H. (2010)
[18] Buri, H. (2010): p.219-223

5.5.2.2. Alucobond pavilion

Using the production knowledge defined in the initial investigations a new research project was devised as a workshop with student participants. The main goal of the workshop was to develop a small pavilion, optimized for the performative material and structural qualities of Alucobond.

Aluminium as a material has a very high specific embodied energy. Although standard Alucobond has only two surface sheets of Aluminium, each at 0.3mm thick, the further processing of the polyethylene core, and the bonding of the composite sandwich all add to the overall embodied energy of the material. The goal of the project was therefore to develop a pavilion that used digital design to optimization of a shell structure, in terms of design, span and coverage/material volume.

Scale models, test panels, and full-scale mock-up tests were undertaken. The pavilion concept was developed as a set of serial standardized arches, designed with the idea that if additional width was required, additional sections could be added on (or removed) at will. The section (arch) was designed asymmetrically (to allow standing on one side and more enclosed sitting on the other side). The strategy for assembly optimization was to make the pavilion from a minimum of very large pieces, so as to minimize the number of required connections.

Through continuous folds across the surface of the pavilion, and due to the angular folded intersections the structure becomes increasingly stiff. For maximal structural rigidity, each of the folded panel pieces has a minimum of two fold sections (in this way the panels are self-rigid across both section and length). With these geometric and folding parameters it was determined that the constraints on the structure would not be defined by the material or the folds, but that the constraints were defined by the available size of the production machine.

The width of the CNC milling machine is 1500mm, and as such the maximum (flat unfolded) width of each plate section was 350mm (four plates across the panel width, leaving enough material on either side for the "tabs" for fastening). The structural depth of the folded V (*sin*width of plate*) determined the maximum possible longitudinal length of a folded plate (worst case would be a flat plate acting as a horizontal beam). The calculated maximal length of the folded panels was 3550mm, however the maximal length available in the CNC milling machine was 3200mm. As such the constraints of production determined the maximum module size for the assembly for material (1500x3200mm).

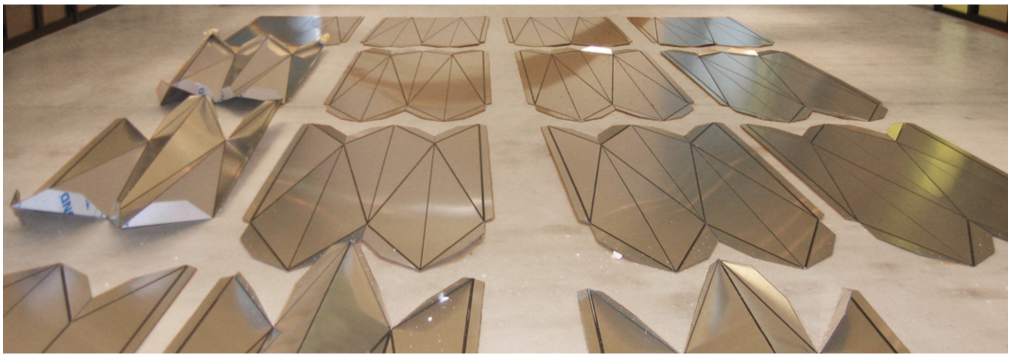


Fig. 5.5.2.1. Fabricated Alucobond plates showing flat and folded states, before assembly

5.5.2.3. Production

As a "proof of concept", the research team and eight students constructed four sectional arches to make a small conceptual pavilion. For expediency, the structure did not include any of the possible irregular or angular parametric geometries, and was built as a straight linear structure. In the final development of the design and construction details there was a significant emphasis paid to standardizing the connections (made with bolts), and ensuring the quality and fit and finish of the final joints.

By using the Alucobond to fabricate a Surface Active Structure System, it was possible to build a pavilion with a span of over 7m and an overall height of 3m from material with a thickness of 4mm. The structure was self-supporting and exhibited no outward thrust on the supporting edges, however a "tie" platform was built and connected for reasons of safety (added stability) reasons of design (addition of the proposed seating area) and reasons of protection (to minimize damage to the thin edge of Alucobond at the meeting with the floor). The amount of "vertical sag" due to self-weight was slightly higher than expected[xxi] (from simulation models and testing), however this was compensated for slightly through post stressing the shell with the tie platform.

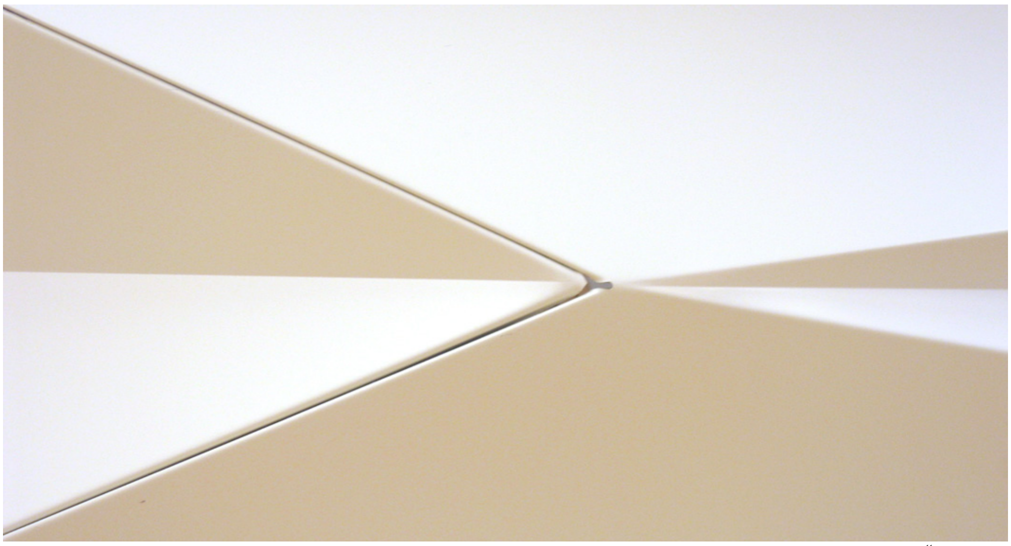


Fig. 5.5.2.3.a. Precision detail: Connection joint between two panels, including stress release "notch".

The project process was all undertaken as a digital chain, with design concept, development, testing, optimization, unfolding, and processing of the data for machining all done using scripted (or semi-scripted for the CAM processing) digital processes. The initial design period was composed of one day for conception and testing, two days for design development and finalization, and one day for preparing the digital files and refining the scripted unfolding scripts. Each of the four composite folded arch segments was made up of four folded panels. Each panel took approximated 10 minutes of preparation and mounting time, and 20 minutes of machining time, for a total fabrication time of approximately eight hours. The total assembly time for the shell structure was 2 days, and one more day for the bench and floor, and final fitting and cleaning.

The final pavilion was designed, prototyped, fabricated, and assembled by the project team; from the paper folding to the opening party, in eight days.

Fig. 5.5.2.3.b. Alucobond Pavilion, as installed at the EPFL ECAL lab. (2008).

5.5.3. Performative Alucobond

The Alucobond pavilion was a proof-of-concept for the digital chain and the integration of digital design and production, however to advance the investigation into the issues of complex processing, additional development of the investigation was undertaken.

The collaboration with Alcan Switzerland progressed with several sessions of research consultation addressing proposed innovations in coatings for Alucobond and providing insight into concepts for future performativity of the material. In a series of speculative workshops the researchers were presented with concepts for new coatings, and asked what the creative and architectural potential of each product might be.

One specific proposal for a "performative" coating was singled out for concept development. The polymer coating is a photo-catalytic film applied to the surface of Alucobond. In the presence of light the coating chemically reacts with the surrounding air and catalyses some forms of chemical and organic pollutions into harmless constituents.[xxii] More simply stated; it is a "pollution eating coating."[xxiii]

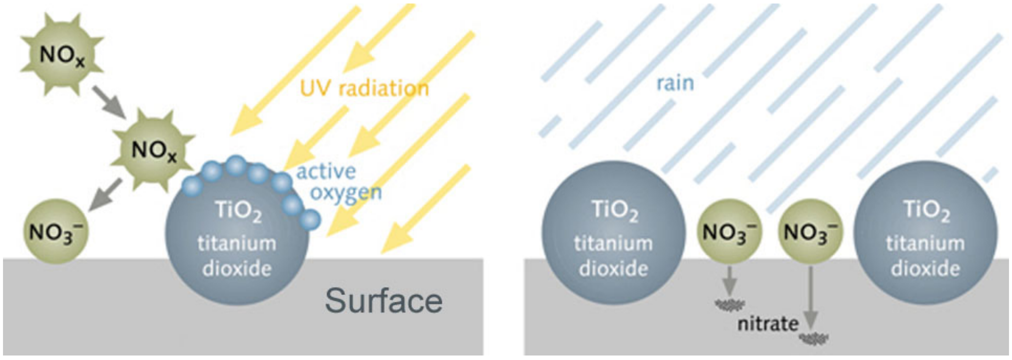


Fig. 5.5.3. Photocatalysis of Nitrous Oxides (and other pollutants) using a Titanium-dioxide coating,

This photo-catalytic process has been used in other construction materials such as concrete, and concrete paver-stones, but has never been used on architectural façade material. Given the large surface area of buildings and high exposure to sunlight and polluted air, the combination of Alucobond with this coating technology has strong environmental potential.

5.5.3.1. Performance parameters

The performative characteristics and parameters of this "new" material change traditional design understanding of "efficiency" for this material. Typically the process of design optimization is to minimize material (less material = cheaper), however, with this performative material, this equation is inverted. The "environmental friendliness" and performativity of the material is directly proportional to its exposed surface area, so this means that the material usage equation is inverted (more material = better performance).

To optimize the coating functionality requires large surface areas, however concurrently there is still a heavy environmental cost in the embodied energy of the material. Environmental performance favours using a minimum amount of material, with a maximal surface coverage. (note: same criteria as for the initial pavilion). The minimizing of any additional structural material makes the use of a folded plate s shell is an ideal application for this photosensitive coating. Including solar parameters into the model dictates that best performance is achieved when maximal surface area is optimized to be as close to perpendicular to the average solar direction, as is possible.

From these parameters the design and performance system became a parametric and geometric problem: How to maximize average solar gain, over a self-supporting structure with maximal surface area.

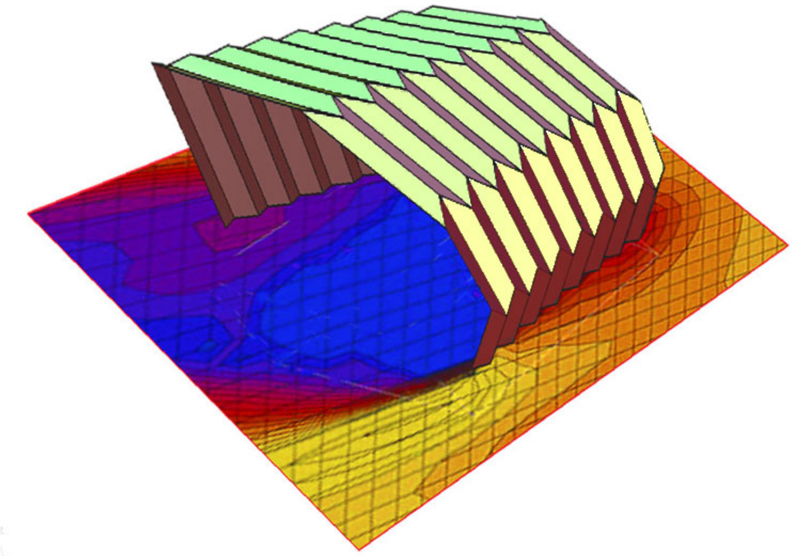


Fig. 5.5.3.1.a. Ecotect composite analysis: Solar analysis of shell surfaces to determine photo-catalytic performance; 2D CFD analysis around structure (wind or rain is required for cleaning of surfaces to maintain photo-catalytic performance)

The geometry of the folded shell structure, although structurally efficient causes the first system contradiction. Because of the folding, each surface cannot be optimally oriented for solar exposure, as such the average of the folded surfaces forming a V will be used.

The second contradiction is that the structural depth of the folds determines the strength (and therefore the span) of the panels; however the more “flat” the panels are, the more optimally they are oriented for solar exposure, and the less likely they will be to “self shade”.

The final contradiction in the system is the clear issue that as the sun transits, the orientation to the sun will change, so the calculation of the overall pavilion form needs to be designed and oriented to optimize solar exposure.

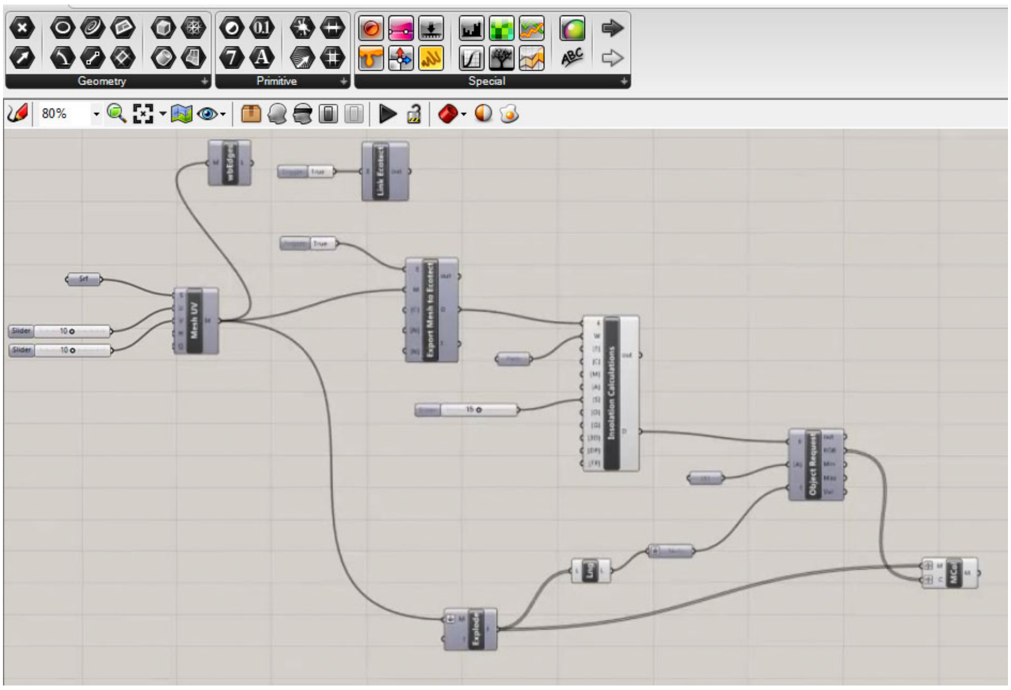


Fig. 5.5.3.1.b. Grasshopper visual script. Use of the GECO plug-in allows for feeding of geometry to Ecotect for solar analysis. The polygon value data-sheet is then returned to Grasshopper as an array.

These relationships and constraints formed the basis for a parametric design that was "graphically scripted" in grasshopper. The solar calculations were processed by Ecotect, but were parametrically controlled and presented in Grasshopper using the Geco[xxiv] plug-in as the data interlink.

The parametric analysis script works by converting the shell structure to a polygonal mesh[xxv] and then porting the polygons to Ecotect using the solar analysis tool. In Ecotect the solar settings used were the location (Lausanne, CH including the .wea weather data) and the solar sky subdivision value for analysis were set to 12 (coarse evaluation). The Ecotect mesh analysis data is then fed-back to Grasshopper (using the "object request" tool from Geco).

The resultant script is an interface that allows for (almost!) real-time digital design feedback of solar data in the polygonal representation of the shell structure. The combination of the feedback from the solar simulation could therefore be used to modify and optimize the structure for maximal solar gain, while balancing the structural variables.

5.5.4. Design conclusions

The results from the environmental evaluation and performance scripting of the project made several geometric issues more apparent.

The first conclusion is that in a "tabular rasa" condition, there is only one optimal shape for the pavilion. This shape is directly biased to the average annual sun-sweep path for a particular geographic location. Therefore all constructs at a specific latitude will have the same shape. The optimal configuration is if the main axis of the vault structure is aligned is north south, and the shell is symmetric. This optimal geometry is only altered in case of additional constraints or any form of solar occlusion in the contextual condition of the location. Because the context then becomes very important to the overall shape of such a performative pavilion, the quality and extensive digital modelling of context become prime factors in the "tuning" of such a design.

The second conclusion is that due to the "folded shell" geometry of the overall structure, there will be areas of the surface, which will be under-performing. Areas where the surface must be folded away from the average solar direction will underperform, as they will be predominantly shaded. For these areas, there is no benefit to using the "special" coated material.

The final conclusion is that the parameterisation of such a environmentally performative design is an interesting exercise, however given all of the constraints experienced throughout the development of the investigations (fabrication, size, performance, and evaluative), the system presents significant challenges. The system as a shell structure (without performative factors) is a viable and very efficient structural system in its own right.

5.5.5. Critical analysis:

> *"Architectural tasks are usually defined by complex networks of requirements. All nodes in this network like program, circulation, light, material, structure, budget etc. are interrelated and interact with each other. Well designed building components never serve only one purpose and practices should seek inclusive strategies that map a multitude of functions to single elements."*[19]
>
> \- Ben Van Berkel

The preceding investigations focused on the concept of a complex and intelligent structural system being composed of a single geometrically manipulated surface. This concept of "multi-purposing" of a single component became the basis for the geometry, but it also advocated the idea that efficiencies come from the intelligent multi-use of a single material. Although this idea was developed at a conceptual level in these investigations, this concept of "multi-purposing" will be increasingly important in architecture.

---

[19] Van Berkel and Bos, (2006).

The investigations in this section were not motivated by functional and aesthetic goals, but rather they were instigated by a singular *structural system*. The associative parameters of this system, combined with materiality informed the possibilities and constraints for the resulting designs: The stiffness and hardness of the materials (carton, paper, and Alucobond) determined the machinability; this defined the "form-ability", and the resulting constraints and parameters of geometry clarified structural potentials. A single focus on a structural system, combined with a material defined the design approach: a *problematic*.

With no explicitly stated design or architectural goal, the project concepts were instigated using *design search*, and then further refined through *design exploration* and *design strategy* methods. From the initial results an informed *start state* allowed for the development of both the architectural project and the use of *processing* and the digital chain for its completion.

Development and building of the Alucobond pavilion was a learning experience. Multiple changes and alterations were done "in action", but through digital control of the output these changes were minimized and were not visually identifiable in the end construction. The pavilion itself was strong, well finished and of high construction quality; attributable to the collaboration of a team where all were intrinsically involved in the process.

"Processing," the capability to manage and coordinate complex data and instruction sets was used to develop the projects, first with a focus on design and fabrication, and then getting more complex to include performance optimization. The focused on performance and how a single material could be manipulated in design led to the development of concepts for a multipurpose role of the material. With the further augmentation of the material into a performative "smart material", the parameters and their effects on the efficiency of the design intensified.

The development of a digital chain is a design problem in itself. The *problematic* asks what production methods and technologies should be included in the process, and the process evolves as *dialectic* with emerging understanding. With such an increase of insight, often the computation results may have become somewhat predictable to the designer; however, the ultimate advantage in design is that knowledge from one project can be applied in the next. In digital processing this advantage is augmented in that in addition to the knowledge, also the scripts, tools, and technical abilities can be applied in the next project.

The development of digital tools for use in design clearly has a longer term affect on a designer and the characteristics of their work. From *plasticity* in *tool theory* we know that the availability of a tool, and the skill to us it affects the approach and work of a craftsman. With a fully developed set of "customized digital tools", a designer/programmer will have a unique approach to different links in the digital chain. With the knowledge of how to connect the links in such a chain the ability to use computation and processing of complex data, becomes a platform for radical innovation.

5.6. Findings

The findings from all of the practical investigations have been recorded at three distinct levels: Pragmatic findings, general finding, and meta-level finding.

The pragmatic findings from the investigations are the results of the project work, and the "lessons learned" over the progression of the projects. The individual pragmatic findings have been documented in each of the three sections on *Control, Predictions,* and *Processing.* The observations from each investigation are useful in understanding how each project evolved, how decisions were made, and how the technology affected the ability to execute the project. These findings are also useful in making conclusions about the overall thesis goal; of determining the current *paradigmatic* position of the digital chain in architecture.

5.6.1. General findings

Six general findings have been identified from the project work. The findings are based directly on observations from teaching and working with "beginner" digital practitioners. These observations provide insight into the problems encountered in experimentation, and the "learning curve" faced by each practitioner. These findings are extrapolated in the conclusions to make a statement about the current state of the digital chain in architecture.

1. Digital design and production work is still fundamentally a critical and reflective process.

It was observed that the use of digital design tools reduced the frequency of self-criticism, reflection, and change of perspective (the "stepping back "from a design). This fact was attributed to two issues: The "perfectness" of the on-screen model creates a false sense of quality; and the dislocation of the designer from the "ethereal" work on the screen creates a dissociation of haptic senses of proportion, scale, and qualitative characteristics.

A practitioner confidence, and their own understanding of their design improved when intermediate "transformation outputs" of the design were done. A change in media from the screen to something physical (renders, prints, models, prototypes) forces a change of perspective; the designer sees the design differently, allowing for reflection and critique.

Example: This was observed extensively in the development of spacing of the geometrical splines in the HBF and Landesmuseum projects. On-screen measurements were abstract and difficult to relate to a sense of final surface quality. This was partially due to the geometry being abstract, and that the final surface quality was physically dependant on the material interaction with tool geometry. The solution was to make fast sets of 1:1 scale prototyping at small sizes, as an immediate haptic prototype from which design decisions could be made.

2. The most successful use of the digital chain occurred when there were the significant design and production constraints.

Design is a process of exploring a problem *and* developing a solution. Constraints provide a limit to the amount of exploration and testing required, and provides stability within normally "ill-defined" design problems. Explicit digital programs work most efficiently when there are explicitly defined conditions and problem definitions. A small amount of subjective interpretation in a fixed design frame allows for subtle, and elegant solutions.

Example: FLOWchannel - the methods, materials, and basic geometry of the construction were predefined, leaving time for the design/science experimentation and development of surfaces. Heavy coordination ensured the quality of the project, without compromising the complexity or individual design integrity.

Constraints may be viewed as limiting creativity, however this is a question of perception by the designer. When creativity and design are successful in a very constrained problem the results are often not only functional, but also "elegant".

3. Design as exploration is a digital form of "brainstorming" in design.

In conditions where there are minimal constraints or no stated method, digital programs, tools and code can all be used for brainstorming. *Design as exploration* is defined as having a clear starting state, but lacks any methodology or goal state. By "playing" with methods, parameters, or associations, new insight into a design can be made (or may be stumbled upon): In the *exploration* process, the modulation of any (non-constrained) parameter or association has potential as a creative motivator in a design approach.

Ex: Initial experiments with Alucobond were an exploration of the material that triggered interest in the previously investigated concept of surface-active structure systems. The progress of the investigation came from developing process based on material and manufacturing constraints. The design was a by-product of these capabilities.

Given that most ill-defined design problems are entrenched in *polysemic paradigms*, it is possible for the designer to re-frame the problem and reorganize the constraints.

Ex: Neglecting the strict historical preservation rules that defined the Historical Building Façade project brief, allowed for a different perspective of the project, and resulted in a new "reinterpretation" concept for what was originally a rigidly and explicitly defined project.

4. Economics still define and influence every aspect of digital design and production. These costs were experienced as time, technology, material and production costs.

The idea of the "paperless studio" and the computer reducing operational costs is false. Output, consumables, and hardware costs from and prototyping are significant and result in greater physical resource use. Physical material costs for prototyping, where methods ranged between: Expensive process and expensive material that took a long time (*ex: 3D printing*), or cheap material, inexpensive processes, and reasonably fast time, but with significant waste (*ex: CNC milling*).

Every machining technology has production costs (access, tools, consumables, maintenance), but the ease of engagement (due to having already created the geometry) is enticing. Use of technologies should be critically "appropriate" (ex: no laser cutting straight lines in carton), with the goal of improving the design, and not only saving time. *Ex: This is a fundamental criticism of 3D-printing technologies: The fact that a model can be printed means that it is not being made by the designer, and this eliminates any possibility of the designer learning from the process of making the model.*

However the greater issue of cost was measured in time: spent in learning new technologies, time spent scripting, debugging, and other problem solving. Because of the explicit and unforgiving nature of digital technologies the medium required care, attention, and diligence: all taking time away from design. As experience improves the lost time is reduced, however the use of digital tools needs to be strategic so as to offset time investment with productivity.

5. Both design and computation are iterative processes, where refinement is a product of multiple iterative cycles. Good design (digital or not) requires iterative refinement.

Digital design software and the "on-screen" representation may be deceptive in that it gives an impression of clean, solid, and properly formed geometry. This fact seems to lead to less "working" of the iterative *reflective practice* loop by practitioners.

Software programming also uses a similar pattern of logical loops, operators, functions and evaluations to iteratively solve encoded problems. This parallel between programming methods and design processes needs to be recognized and used to reinforce the process of iterative refinement in design.

Ex: The Rustizierer project worked at several optical scales of resolution. Reciprocal "Hilbert curve" algorithms were chosen as one of the development cases so as to use a geometric system that operates at different iterative levels. The result of the code was a graphical representation system that scaled and multiplied the reciprocations as added detail of representation was required. The code written for design was efficient as it was able to use more detail (and cycles of refinement) where required, and less where there was less detail.

Digital design tools, and the concept of the digital chain do not replace the *reflective practice* design loop, they are able to make it more efficient, but working and refining a design are still required to ensure quality and appropriateness.

6. Designer intervention in the processes is still fundamentally required.

Despite making specific attempts to automate the digital chain, critical human intervention and correction brings value to a project. When the digital chain is completely automated, there seems to "loss of authorship" in the design result, as all of the investment has been made in the code. The ability to make instantaneous parametric variations also reduces the value of the results.

Numerous perfect results are not interesting; it is elegant results that satisfy designers. Elegance is making high quality design that manages complexity, but is not complex itself:

"*Elegance articulates complexity.*"[xxvi] An elegant solution displays the intelligence and reflection made in a solution, and this value enhances designer authorship.

Given that architecture is typically validated from a rhetorical stance, the digital chain needs subjective human intervention to give it the *ethos and pathos* that digital computation cannot provide.

Ex: These finding are derived from experiences with all of the student design-build projects, but most notably from the FLOW and Alucobond Pavilions. Without a passion for their own designs and the overall project the participants would not have invested the extracurricular time to complete the group project. In contrast the experiences of building the LCH panels was far less interesting as the projects were focused on complete automation of process.

5.6.2. Meta-level finding

The Meta-level findings are insights and observations made on the challenges of reconciling theory and concepts with digital technology. By using the Digital Design and Production courses (DD+P) as a basis, the principal investigator was able to observe many subjects experiencing the "digital learning curve."[xxvii] The compilations of experience reveal a series of findings that specifically address the issue of digital technologies and its impact on the formulation and influence of theory and abstraction in architectural design and production.

From these observations nine findings have been summarized which relate to the ability to develop theory and conceptual work using digital tools.

1. Technology is a parallel field in which to both develop and implement theory.

Technology and the working with tools is conceptually viewed as being separate from the practice of architecture. As theories are developed about the tools, data, or technic, the capabilities in turn influence the working concepts of design. Although the two sides are conceptually distinct, an abstract association can be instituted leading to new design theory.

2. The digital medium is explicit; it does not support "vagueness".

Abstraction and conceptual thinking are more difficult to develop while working directly with digital tools (compared to sketches or sketch-models); due to the explicitness of information required to represent a phenomenon. We found that users were reluctant to give explicit form to anything that needs to be conceptually abstract (such as a parametric model), for fear that the initial definition will affect later conception or perception of it as it changes.

3. Architectural theory derived from technological capability is inventive, but if done simply, then it is elegant.

Elegance is a virtue in programming, and is used to describe when a complex operation is encoded in a simple manner: it is a qualitative measure of how cleanly a program deals with complexity. Elegance in design is a measure of sensitivity, restraint, and functional competence, but also beauty and awe. In both cases, when a result is seen to be elegant then it has more persuasion, it resists critique, and therefor has more potential.

4. Solution converging methods are good for problem solving, but impractical for theory.

The *Design as planning* (rational solving) and *Design as strategy* (incorporation of abstract concepts) methods are convergent methods predominantly used in digital design for problem solving, and as such both methods are not conducive to developing new theory. *Search* and *exploration*, are divergent methods, and therefore promote new conceptual thinking about the design problem. Developing new digital based theory is easier if the method is conducive to generating and manipulating concepts, rather than converging on solutions.

5. Systems thinking is dependant on understanding the morphogenic quality of data.

If *any* characteristic can be codified or quantified as data, then it may be used in an associative algorithmic relationship to define any other abstract phenomenon. The system (design choices and associations) need not be rational; they only need to be explicit. The concept of abstract associativity can be used to invent thought-provoking and very creative associations.

6. Architecture needs to be able to accommodate failure. Digital architectural design should also include the ability to "learn" from failure, and to use it for constructive refinement.

Unlike design, even advanced programming is not able to creatively deviate from its process; all possibilities of methodological progress have already been encoded. As such, programming systems can be conceived of as binary, rather than qualitative. However, it is important that in design there exists the possibility to fail; "failure" is not an end state, but it provides a learning point, and it redirects a conceptual process back towards iterative improvement. Failure in programming stops the process, whereas, failure in design is an iterative step and can be used constructively.

7. Simulation and performance are used to justify design; this is superficial.

Design is fundamentally about authorship, and as such simulation results should be used to inform design, but not create it alone. Quality of design comes from rhetoric, so the designer needs to convince a viewer that the design is an intelligent solution, one that has been reflected and evaluated with multiple perspectives, and criteria. Performance evaluation is one of many overlaying scales and influences, but for a design to be robust it must engage multiple influences at a range of scales.

8. The stopping point is a design decision.

Designers progressively engage and refine a design solution until a specific criterion is satisfied. In digital design, the use of feedback or logical looping is used for similar cyclical processing and refinement. In programming, stochastic methods and logical loops are used for optimizing, solving or refining data. The fundamental problem in all three processes is the "stop" decision. What is the subjective criterion to "stop" the iterations? When the stopping point is a human intervention in a digital process, this transfers a subjective responsibility to the designer, but it also brings authorship and added credibility.

9. Changing understanding of systems theory and technology will require a rethink not just of theory, but of the role and methods of theoretical engagement.

New architectural theory is often an attempt to re-address key concepts of past architectural theory in a contemporary context. However the current technology is an intellectual technology. As an intellectual tool, the computer changes the way we think, and insomuch, it seems unproductive to reposition ancient theories into new technological contexts, when the methods of thought and epistemology has changed.

Computation is a significant tool to design to model, however with the possibility to model "behaviour" and time-based process, the conceptual model has changed. The resulting knowledge from such processes is fodder for new theories and architectural concepts

These findings, at both the general level and the meta-level, were derived from practical investigation work, both with students, and as a researcher occurring over a five-year period. These observations were framed in a variable and subjective context of both evolving technology and changing design methods (typically using reflective practice), so they are not empirically validated, but rather are based on cumulative experience. The findings as stated assume that a modus of *rhetoric* is the basis for architectural value.

5.6.3. Evolution of technology over the thesis period

The investigations for this thesis, from the first projects to the current time, have covered a period of slightly less than ten years. The basic principles of computation, architectural design, and fabrication technologies have not fundamentally changed in the past decade, but the access to power, speed, and capability have: both software and hardware have improved and programming and data handling have also matured significantly.

When the investigations began MAYA and MEL were the predominant "experimental" CAD software. In 2005 this was switched to Rhinoceros, and in 2008 RhinoScript was supplanted with the Grasshopper visual scripting interface. All of these digital software changes caused minor bifurcations in the digital working methods, and learning curves for practitioners.

The fabrication technology has changed less over the thesis, but as the laboratory purchased new machines, the new access also caused changes to working methods. The shift from 3-axis milling to 5-axis milling brought new potential to the investigations. The availability of water-jet cutting provided a full-scale industrial analogue to the modelling laser-cutting machine. Each change also allowed for new materials to be used, and new forming processes to be included in the working process.

All of these changing parameters make the investigations and findings highly subjective. With each change in "scientific parameters" the empirical objectivity of an experiment is compromised. There is no consistent basis from which to make all of the conclusions, …other than the fact that the profession of architecture also works in a field of constant technological change. The fact that the working context of the laboratory was in a state of constant change is actually similar to the professional context, and makes the resulting findings justifiable.

Endnotes:

---

[i] See section 2.4.5. Warren Weavers definitions of complexity.

[ii] See quote from Gropius, section 2.3.1.

[iii] See section 3.3.1.4 Disappearance of the draftsman.

[iv] A detailed list of collaborations is posted in the appendix.

[v] As seen by the author at the MOMA - Museum of Modern Art, New York.

[vi] Note: It should be stated at the offset that several of the projects in this section were conducted in collaboration with Dr. Kai Strehlke, who's doctoral dissertation was entitled *"Das Digitale Ornament in der Architektur, seine Generierung, Produktion und Anwendung mit Computer-gesteuerten Technologien" (The digital ornament in architecture, its generation, production, and interpretation with computer controlled technology).* This dissertation presents the common projects in a more comprehensive manner with specific focus on development of technologies. For further reference and greater detail of explanation, these sections are referenced, but not duplicated.

[vii] Ex: Gottfried Semper's theories of ornamentation had at ground level highly rusticated stone work. Moving up the façade the ornament became progressively more refined and artistically controlled. At the top of the façade, closest to heaven, were the most fine and "civilized" ornamentations.

[viii] From personal discussion, translated by the author

[ix] For a detailed depiction of this project, and more detail on the specific issues of technology, see the project PhD dissertation: Strehlke, K.(2008).

[x] This script was developed and written by Kai Strehlke

[xi] See section 5.3.8 "The Rustizierer "

[xii] Using the definition of control that implies *verification*.

[xiii] Developing a predictive hypothesis, devising an experimenting to test the hypothesis, and using the results to build a better conceptual model for further prediction.

[xiv] Investigators: S. Albrecht, M. Hochuli, T. Kamp, M. Knauss, S. Oesterle, R. Scherrer, L. Sonderegger, S. Walker, J. Weiss, K. Zech

[xv] With exceptional collaboration, input, and assistance from Dr.J. Bruehler from the Institute of Hydromechanics at the ETHZ.

[xvi] "Processing"(process) should not be confused with the java based scripting language of the same name.

[xvii] These images are in the original 1967 publication of the book, however and unfortunately, they were not included in later revisions of the book.

[xviii] This was a diplomwahlfach arbeit research project given by the author and developed in collaboration with student, Marcus Giera.

[xix] The phase of a wave is scientifically defined as the initial angle of a wave at its origin. This is not the definition of this value in our system, however given that the change in this parameter, also changed the angle, the term was adopted as nomenclature in the script.

[xx] Other than setting the basic power and speed that will cut the material.

[xxi] Likely due to compounded reduced stiffness at the joints; material weight causes the folding to flatten, the intersection of the joint becomes less stiff (less structural depth), and this contributes slightly to sag.

[xxii] Ex: nitrous oxides (NO_2) are converted into nitrates (NO_3) which as a solid is washed off the surface.

[xxiii] For full info see: http://www.mandalaconcrete.com/photocatalyticconcrete.htm

[xxiv] Geco is a free download at: http://utos.blogspot.com [12.05.2011]

[xxv] Required for Ecotect, but also to minimize the size of data and make the process conceptually efficient.

[xxvi] From Patrick Schumacher, in "Design Engineering AKT":p.68

[xxvii] Approximately 150 students over 10 years of teaching DD+P courses. See appendix for notes and observational records.

6. Conclusions

The principal question of this thesis asked; has the evolution of digital technology established a new paradigm in architecture? The conclusive answer to this is "no". The reasons for this conclusion are both semantic and deductive.

From the epistemological research, this thesis has established that digital technologies and specifically the implementation of computation methods into design, allow for more complex and methodological approaches to design. Through computation, methods of *systems thinking* and *reflective practice* can be revised to function at higher levels of complexity and with greater ability to associate qualitative and quantitative parameters into the design and ensuing construction systems. This added capacity also allows for greater abstract associations, and a wider range of potential for the implementation of architectural theory. These technologies and their capabilities represent a *disruptive technology*, one that is changing the workflow and working methods of architects. However, with this said, the two primary conditions for a *paradigm-shift:* a fundamentally radical innovation, and its accepted adoption into architecture, have not yet been met.

6.1. Bifurcation

In this thesis, digital computation has been used for the *control, prediction,* and *processing* of complex data in design. Production technologies (although not radical innovations themselves) have been shown to change the relationships of practitioner and technology. Each of the digital capabilities constitutes innovation, however each alone does not constitute a paradigm-shift. Digital tools, and specifically computation-based methodologies are a *disruptive innovation;* as they change the vector of productivity. The fact that these technologies qualify as a disruption of practice indicates that there has been a *bifurcation* of architectural process. Although the majority of practitioners have not yet adapted digital computation and computation based design methods into practice, the mere existence of the technologies and methods creates the possibility for a *paradigm-shift* to happen.

However the thesis statement asks: "has a paradigm-shift occurred?" The negative answer to the thesis questions is due to the semantic definition of paradigm-shift as requiring *mass acceptance*. The fact that a majority of contemporary buildings (including those in process) are still predominantly built using the traditionally established methods of projective geometry, and built using well established materials, and technologies denotes that "mass-acceptance" has not yet occurred. Although this is a simple and semantic reasoning, it cannot be overlooked in validating the final conclusion for the thesis.

6.1.1. Reality of the digital chain

The digitally computational processes of design programming, fabrication optimization, simulation and feedback, project management, and construction verification all exist and are established technologies. "Proof of concept" projects have been achieved in academics, and in the making of architectural components or parts for larger projects. In the profession, the uncompromised use of computation within the digital chain, including digital management and execution of complex projects is still rare[1]. Through the findings and observations of this thesis, five principle reasons for this have been identified:

6.1.1.1. Coordination

The contemporary practice of architecture has evolved from a top-down control model (the master builder) into the current model of dynamic team collaboration. The architect cooperates with specialists, consultants, and service providers; and may (or may not) be the overall project coordinator. As such most project structures can be understood as progressive

[1] Arayici, Y. et al. (2010)

"chain" (or in complex projects a network) of team members, and the linear sequence of work that they perform.

The digital chain functions most effectively when all "links" are coordinated such that their data is able to flow bi-directionally. This exchange of data requires significant management of workflow, scheduling, and data (in both type and structure).

> *"...implementing BIM effectively requires significant changes at almost every level within the building process. That is to say, it does not only require learning new software applications, but also how to reinvent the workflow, how to train staff and assign responsibilities, and changing the way of modelling the construction."*[2]

Building Information Model (BIM) software is proposed as a digital system to manage and control such flow and interaction of information within a project. A BIM is both a model, and database of pertinent information, however this combination introduces its own learning curve, and such proprietary software brings its own constraints to working methods. For this reason (amongst others) architects have shown reluctance, and have been slow in adopting BIM as a design platform or management technology[i].

> *"Despite these challenges, 34% of architects are using some form of BIM modelling. But for most this is only during conceptual stages to generate rudimentary cost data and quantity take-offs helpful in evaluating the expense impacts of various schematic designs — not for full BIM production."*[3]

Technologies to coordinate workflow in a project will continue to develop and mature; however given the precedent of technology adoption, it is not likely that architects will the software for reasons of efficiency or creativity, but rather the most likely motivator for large-scale adoption will be regulation, as many civic jurisdictions around the world now mandate specific (BIM) formats for submission of building permit applications.[ii]

It is concluded that technology will change the traditional interactions between team members, whether this is a result of conscious implementation of the digital chain or not. Through the early inclusion of "downstream" members of the project team (suppliers, fabricators, contractors), their working parameters can contribute to design decisions. Although this appears to be a logical decision, there are many "non-procedural" reasons that this idea has been resisted or that it has not occurred; specifically the issues of economics, business models, and legal issues related to design and production responsibility.

6.1.1.2. Business

Although business models were not explicitly investigated in the thesis, the models and their impact on the delivery of projects were presented and considered. The working experiences conclusively show that success of the digital chain is dependent on an agreement of goals, motivations, and collaboration within the team, all fostered by technology. Although this also seems logical, these three factors are quite subjective in the context of current professional "project delivery models".

The most popular project delivery model for architectural projects is the *Design-Bid-Build* (DBB) method. The advantages purported in this model are that it fosters price competition, and therefore economy. For the digital chain, however this model also reinforces the division between design, consultants, and construction[iii], and inhibits meaningful critique, and reflection from production feeding-back into design.

Alternative project delivery methods include *Design-Build* (DB), *Design-Build-Operate-Maintain* (DBOM), and *Integrated Project Delivery* (IPD). These methods (variably) view the project as a unified team process, and as such are more suitable for the integration of the digital chain. These methods do have potential for added creativity and optimization,

---

[2] Arayici, Y. et al. (2010)

[3] From: Gonchar, J.(2008).

however; typically in these methods the architect is not the oversight for the process. This fact raises concerns on issues of design authorship and credibility in the thesis.

The stated goal of this thesis is to examine technology as a creative potential within design. The *integrated project* methods all support refinement of design with technology, however their objective is typically economic and process optimization; often at the expense of creativity and authorship. Architects are typically responsible for design, so their technical ability to engage in such *delivery models* is a strong determinant of design quality.

This thesis does not propose that the digital chain can change the models and interrelations of the business models, however it does show that design quality can be supported without additional cost, through creative use and coordination of technologies.[iv]

6.1.1.3. Responsibility

The digital chain disperses potential influences for a design across a wider range of the team. Digital design concepts acknowledge that disparate parameters can be used to affect design process, and also the design itself. As such, the "supervising oversight" for the methodology, hierarchy of influences, and the flow of data becomes a vital role.

With the inclusion of parametric, generative, or algorithmic design programming in a project, this emphasis of work in the "lead" role may shift from being a creative task to being a supervisory task. Given that within a digital chain, disparate data sources and team members may be able to "autonomously" alter the end state of the design, managing input data is fundamental to the creative process, but also for reasons of validation and error checking.

This influence perhaps can be best understood in the area of production. The traditional methods of oversight in production were the creation of "shop drawings" by knowledgeable technicians. This process was time consuming, but had the secondary function of being another check or "filter" to catch design errors or mistakes before they are (expensively) committed to physical material. In the digital and autonomous process, where the design data is used to automatically generate "cutting files" for production machines, this stage is eliminated, allowing for significant cast savings.[v]

The former methods favour human *interpretation*, while the new technologies are an automated form of *translation*. In such a process with many authors, if there are errors of parameters, geometry, or code then "*where does the responsibility lie?*" In 2009 at the ACADIA conference this question was posed by Dr Kai Strelke[vi] to digital practitioners and fabricators, the reported answer did not concisely address the question, but was simply stated as: "*Don't make mistakes!*"[vii]

The implementation of technologies that dissociate a practitioner from the direct control of their craft poses problems of responsibility. Additional technologies can be used as monitors, supervisors and "digital oversight processes"; but with this argument there is a risk of spiralling into a circumlocutory discussion. As technology improves, the robustness of error handling increases, and this may prove to be part of a future solution; however for the moment responsibility of design and production is still a very valid and real concern.

6.1.1.4. Availability

A final observed difficulty to broader implementation of the digital chain is the access to technology; not specifically the availability of computers, software, or machines, but rather "gatekeeper" issues of being able to successfully and effectively engage such technologies.

The digital chain is based on the concept of mutual collaboration and engagement between the various processes and experts represented by each link. For the digital chain to function viably the links must integrate symbiotically. The traditional role of a consultant is one of being a "responsive" service, rather than being proactive. If then each link in the chain is reluctant or "protected" and the processes are not transparent, the overall concept does not find the synergetic connections that justify the process.

6.1.1.5. Flexibility

More pragmatic is the issue of "flexibility of process". The availability (and collaboration with operators) of specific technologies, machines, processes, materials,… may be integral to a specific project definition within the digital chain. However, as has been previously determined, design is an *exploratory* process; as the knowledge of the problem and context evolves, new understanding redirects and reshapes the goal state of the project. If a project is initially developed for a specific technology, and then through development that technology becomes inappropriate or redundant, then the digital chain will also undergo a shifted state. Optimization of the digital chain is typically dependent on early technological definition, so, such a change of production process may invoke the possibility of cascading of parametric changes and potentially a loss of value. This can be accommodated for in programming for extraneous flexibility, however this (potentially redundant) cost reduces the overall efficiency.

To institute or change traditional working relationships in a collaborative model is a significant challenge. The changing of the technology, the structure of the team, and also the flexibility of their professional psychology may require significant demonstration of advantage and payback. The ability to deal with larger, more complex, and therefore higher calibre projects may be one level of compensation, but motivations for the digital tools and benefits of collaboration need to be proven at multiple levels. Additional "future incentives" for adoption will be proposed within the discussion section of this thesis.

6.2. Reflective Practice

Due to the unstructured approach of *Reflective Practice* and its emphasis self-regulated methods, the process is structured, but flexible. From the research and experiences of this thesis work it has been shown that the integration of new technology into the concepts and methods of *Reflective Practice* does not fundamentally change the established design theory.

Reflective Practice is used as a method of practice and evaluation in many different professional disciplines (both within and outside of design) where the tools, context, and goals are vastly different. *Reflective Practice* is not a design process; rather it is a learning and guidance process with the aim of enhancing informed decisions. Because design is both productive and exploratory, it too is a learning process where growing knowledge modifies design direction and intentions. The subjective "free-association" style of reflection promoted in *Reflective Practice* increases the artistry, robustness, and intricacy of a design method, but all of this is independent of technological tools.

Digital tools can compliment reflective practice, as the technologies are also exploratory in nature, but the process still relies on a human designer for guidance and critical reflection. The two modes of reflection (*in-action* and *on-action*) are forms of analysis, and may be partially computational, however the qualitative valuations still rely on the perception and intuition of the practitioner, and as such they may be collaborative with technology, but not autonomous. Each method used in *Reflective Practice* has structural parallels with analytic and logical processes used in computation, however the main differences are that technology cannot make the abstract and subjective associations required for perceptive reflection.

As digital programming advances, more "creative" procedures for "pseudo-abstraction" and the creation of computationally controlled complexity are being used in design (ex: genetic algorithms, chaos theory). The incorporation of such methods, along with digital pattern recognition based "learning", and higher orders of digital feedback, may (yet) allow for more abstract and "creative" digital methods in the future.

Reflective Practice is a model for practice, but is also a validation of the need for more symbiotic interaction between designer and technology. Technologies may assist and optimize the architectural process, but as long as creative and humanistic qualities are valued, technology will need the *pathos and ethos* of the designer to produce quality design.

6.3. Paradigm shift

A *paradigm-shift* is simultaneously a mutinous and a social event, in that it requires radical change of understanding but also subjective acceptance and social enthusiasm. *Paradigm-shift* is fundamentally based in the principles of *logos, pathos, and ethos* from *rhetoric*.

In the creative fields, iterative technological innovation occurs continuously;[viii] partially as a consequence of design *exploration*, and partially as a by-product of the competitive nature of practice. By definition, radical innovation destroys iterative continuity; once established, radical change causes contextual instability, and the market will either adopt it, or reject it.

Current architecture is still conceived as functional but static enclosure, its interior is still mediated by separate but integrated conditioning systems, and materials are predominantly the same ones that have been used since the industrial revolution. From a highly pragmatic perspective, the current use of digital technology has not instituted radical innovation.

6.3.1. Contributions to the State of the Art

The results of the overall thesis mirror the goals stated for the practical investigations: Contributions to existing knowledge of digital design and production at the levels of pedagogics, practice, and conceptual development.

At the pedagogic level, the thesis has contributed to technological methods and the learning and general development of digital design and digital production in architectural education. As a progressive field of investigative teaching, digital design and production is an emerging field at many institutions. Through the build-up of technologies, concepts, and machinery this work has significant insight and uniqueness in this field of teaching and implementation.

At the level of practical development of process and theory, the work has been established as innovative through peer-reviewed publication of findings in papers and academic journals. The development of digital image based design has been published in the *International Journal of Architectural Computing (IJAC)*[4], and (at the time) was a novel approach to intuitive data management and manipulation of complex geometry. The range of methods and techniques developed in this work have been directly targeted at designers and creative professional, and have contributed to learning, teaching, and the formation of new architectural practitioner. The technologies and concepts developed in this work has also led to direct professional commissions (three documented here, other undocumented), and the projects, their documentation, and the codes and scripts have been used and cited in other papers and journals.

The concept to combine rationalist methods with design process, and specifically the analytical integration of digital simulation into design (from FLOW), was adapted for continuing teaching, and development in the ETHZ Landscape architecture studio.[ix] The digital processes of modelling and simulation had been undertaken elsewhere previously (including by the author at the Center for Landscape Research – U of Toronto), however the innovative augmentation was the use of digital fabrication as an analytical and physical method of validation.

The structural system developed for the Alucobond investigations (in collaboration with Dr Hani Buri), was also a digital evolution of existing knowledge. The codification and digitization of the existing scheme provides architects with new tools for creative expression of folded structural systems. When this structural definition is combined with performative feedback, the project demonstrated a new approach to form development that is rooted in performance at many interrelated levels. The use of digital design to manage this complexity reveals potentials for both creative expression and optimization.

The contributions of this thesis work are not a single specific discovery, but rather a network of interrelated findings that validate the use of technologies in the contemporary practice of

[4] Loveridge, R. and Strehlke, K. (2006),"The Digital Ornament using CAAD/CAAM Technologies "

architectural design and production. Combined, these conclusions show that there has not yet been a paradigm-shift in practice, but they do indicate that a significant and radical shift of technology is likely.

6.3.2. Significance of the thesis findings

The findings of this thesis do not satisfy the initial thesis question, but instead they invoke a new understanding of the current general state of digital technologies and their use in architecture. The final findings of this thesis, do not answer a question, but the conclusions do propose a change in the philosophical relation between technology and architecture.

The current understanding of technology is that of “a tool”, however digital technologies are becoming ubiquitous and transparent to daily life[x]. This thesis proposes that this digitally mediated manner of controlling complex phenomena will extend to architectural design and production, and that soon the “tool” will become transparent. When this happens, the technologies being used will take on a new role as an “assistant or partner[xi]” and that it will be inconceivable to practice architecture without digital processing and computation.

The support for this conclusion is two sided:

On one hand, this investigation has not only provided awareness of contemporary practices of digital technologies in design, but it gave insight into the rate of change of adoption and skills of incoming practitioners. The evolution of technology over the thesis has been noticeable and significant, and this change has been matched by equally intensifying intuitions and skills in the leading edge of student practitioners. If design is fundamentally based in the area of *rhetoric*, and if *rhetoric* is itself fundamentally a collaborative and consensual method of determining truth, then the use to the digital technologies will need to address this.

On the other hand, this research has revealed methods for predicting future technologies. Technical innovation in architecture has typically been a process of “repurposing” existing technologies; by combining this with an understanding of *rhizomata* this thesis develops a prediction method for the architectural paradigm. Although it is impossible to specify “when” such innovations will become entrenched, it is adequate to admit that innovations have already had *disruptive* and *radical* an influencing potential.

Given these conclusions, we are then compelled to ask, what change would constitute such a radical innovation, an acceptance of change, adoption of technology, and ultimately a *paradigm-shift*? This issue is examined in detail in the *thesis discussions*.

Endnotes:

---

[i] For a good overview of BIM critique, see: Celento, D. (2007). "Innovate or Perish

[ii] "... the US General Services Administration (GSA) has required architects to perform full BIM modelling on selected projects since 2003 and is now requiring partial BIM models on all federally funded projects, and is considering full BIM for all future projects" From: Silver E. (2007), "*GSA to Require Building Information Models*," Engineering News Record, Jan, 2005.

[iii] Note: These were also the problem identified in the downfall of craftsmanship and the dissociation of the designer from the *homo-faber*.

[iv] ...and potentially with savings: Landesmuseum, HBF Project.

[v] In 2004, the "file to factory" cost for the project "A-wall" project by SHoP architects was at 25% of estimated traditional fabrication and construction cost: a cost savings of 75%. ref: Garber and Jabi (2004).

[vi] Head of design technology at Herzog and de Meuron.

[vii] Paraphrased from the lecture: "Digital Technologies, Methods And Tools" given at the 2009 Association for Computer Aided Design In Architecture conference, SAI-Chicago, October 10, 2009.

[viii] For proof of this statement I submit any of the annual proceeding from ACADIA, eCAADe, or CAADRIA conferences.

[ix] The waterscapes courses of Prof Girot, continued with the same methodology for three studio sessions, after the lead investigators departure from the ETHZ.

[x] Ex: Personal communications, smart phones and the management of information.

[xi] Ex: Just as "Siri" the personal digital assistant is used with the iPhone.

7. Discussions

7.1. Exponentiation

"Designing is a conversation with the materials of a situation"[1] – *Donald Schoen*

The industrial revolution is cited as a prime example of radical innovation, which changed possibilities, methods, and concepts of design and production.[2] New engineering knowledge was combined with novel maschinic processes (powered tools) to induce a modernization of style and structure in architecture. The developments of technology influenced fabrication and construction, but they also led to radical change in conceptual thinking in design.[3]

The paradigm-shift of the industrial revolution was not solely based on the radical invention of mechanical power, but rather it became possible due to the amplification of innovation resulting from broad industrial and scientific communication.[4] The exchange of ideas between the disciplines of design, technology, science, and industry, was encouraged by the great productivity and financial profits; however, the innovations themselves were advanced by productive exchange of intelligence (either sharing or stealing!). The primary topic of knowledge for such exchange was production methods: the transformation processes to be applied to the states of the three production *rhizomata*: *matter, energy,* and *information*.

It was the newfound methods of energy transformation that enabled the inventions of heavy machines, and such machines then enabled the processing of heavy materials. Each phase of innovation supported the next in a continuous feedback loop, resulting in new or updated materials and processes that enabled radicalized architecture and design. But it is important to understand that it was not a science and engineering advancement that motivated the process; the industrialization of the steel, glass, concrete and the wood industries made the new forms of architecture possible, but it was architects, designers, and industry who made the initial demands for these innovations.[i]

In investigating the relationship between design and industry, and between science and technology, it is tempting to take a single perspective of a "push-hypothesis," whereby science pushed technology, which in turn pushed design and industry towards innovation. This linear model is however too simple and lacks both historical validation and a complexity that addresses the interrelatedness of the four disciplines, and their practitioners.

7.1.1. Contemporary revolutions

A similar chain of events is occurring with the development of new materials. On one hand, new materials are being imbued with performative qualities that extend their interactions to chemical, optical, and even haptic characteristics; however, on the other hand the motivations for discovery are originating not from science, but from the needs of design, engineering, industry, and even in societal expectations initiated by science fiction and popular culture.

Because the subjective, tactile, haptic, and experiential characteristics of materials is still so ingrained to design, it can be argued that such materiality can "ground" the digital design from its non-material digital state. Modelling these processes in digital design allows for analysis and feedback of data between performative and geometrical modifiers, but the physicality of material reinforces physical issues back into the design problem. With insight into new and advanced performative materiality, and with understanding of design and production technologies, an interesting symbiosis for revolutionary design can emerge.

---

[1] Schoen, D. (1982): p.78

[2] See "Appendix 02: The Industrial Revolution"

[3] Hall, A. Rupert, (1974)

[4] See "Appendix 02: The Industrial Revolution"

The theory of the *rhizomata* states that industrial development can be understood as the conceptual multiplication and application of *matter, energy* and *information*. This concept developed by Weiner, refined and updated by Paulinyi[ii], and validated by Schindler[5], provides a method for understanding potential advancements of technology. The ability to predict is still speculative, but it is also now an informed and refined speculation that can provide credible answers to questions of "*what if?...*"

When this question is combined with the understanding of exponentiation, and explorations of other sciences and industries with an eye to the "trickle down" theory, a potential image of (near) future technologies in architectural design, production, and construction emerges.

7.1.2. Technological evolution

In his book *The Shape of Things: A Philosophy of Design,* The technology philosopher Vilém Flusser uses this concept of *exponentiation* to demonstrate that the evolution of production technology has gone through four clearly defined paradigm-shifts. These shifts are identified as: hand to tool, tool to machine, machine to powered machine, and powered machine to controlled machine.

Flusser denotes each of these transformations as a different "*industrial revolution*", as each changes the nature of action, control, as well as the capabilities of the user[6]. Flusser defines the first transition as *empirical*, the second is *mechanical*, the third is *functional*, and the final is *cybernetic*. Each transformation is an evolution of the *order* and *complexity* (according to Warren's theories of complexity), and a transformation of at least one of the *rhizomata* of *matter, energy* and *information* onto the proceeding phenomenon.

- Hand: This is the root state of any work being done, where matter, energy, and information are all in their host state in the craftsman.
- Hand > Tool: application of energy onto matter, such as to shape the matter into a form that will allow the craftsman to work with a higher output capability.
- Tool > Machine: application of information onto a tool or multiple tools, such that the organization of parts allows for additional work and coordination to occur.
- Machine > Powered Machine: This is the application of energy to a machine, such that the machine is able to function at higher power, speed, or duration.
- Power tool > Robot: This is the application of information to a *powered machine* such that the machine is controlled by a flow of information which directs the machines functions, and allows for greater control, and functionality of the machine based on available information.

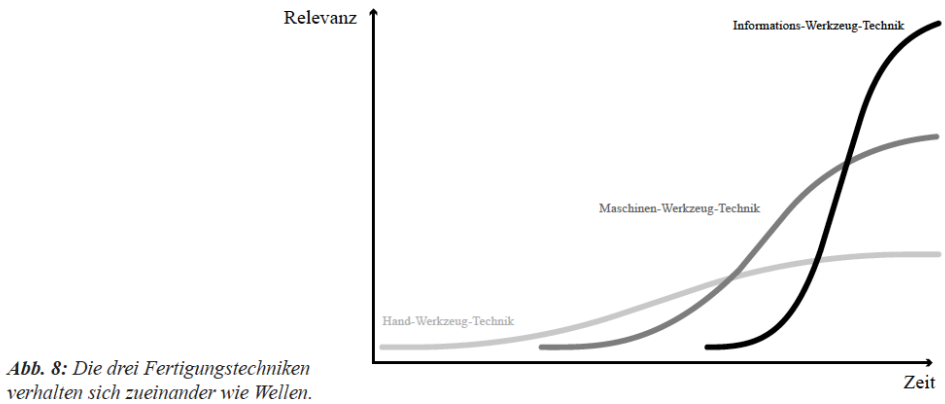


Fig. 7.1.2. Industrial relevance of tool development over time. (ref: Schindler, C. (2009): p.88)

Schindler explains the exponentiation of production technologies by graphing the relevance of technologies and their use in improving productivity. The graph reveals the development

[5] Schindler, C. (2009)

[6] Flusser, V. (1999): p.45

of the different phases of hand, machine, and CNC tool use, and the crossing bifurcation points in the wood working industry. Each transformation is *disruptive* to the industry, but each does not constitute a revolution; for example: after the development of machines, hand tools still have relevance. Each development builds upon the potentials of the previous technological state (ex: Robotics can only be built through the use of powered tools), but this does not negate the value of the previous technology. The paradigm-shift only occurs when the previous state is deemed to be obsolete or irrelevant.

7.1.3. Control: development

As computation increases in processing power, greater complexity of control systems are possible. Contemporary robots control systems are based on electronic feedback, but now include algorithmic "prediction" methods that "look-ahead" in the production code to determine the electro-mechanical requirements for acceleration and deceleration. Advanced control systems now being developed are including fuzzy-logic algorithms for predictive movement control and optimized positioning. Other advanced programs are experimenting with behavioural and control patterns derived from neurophysiological and biological theory; allowing for the robots to monitor their surrounding, and respond to changing context and "learned" behavioural patterns.

With the emergence of controlled (semi-autonomous) tools and programs, the transference of explicit instructions is removed from the job of the "supervisor" and is integrated as a task and responsibility to the designer. Just as the CAD software automated the job of depicting geometrical information in design (and eliminated the draftsman), the popularization of automated digital fabrication technologies is reducing the role of the technician and factory worker. Such developments justify Flusser's comment that "*as our scientific understanding changes, so too do our tools, and our relationship to them.*"[7]

7.1.4. Prediction: new practice

If there is to be such a redirection of practice: if the designer and maker are to recombine through the capabilities of technology, then what will be the outcome for architecture? What possibilities will emerge from the newly empowered *craftsmen* when they are provided new materials, controlled machines, and capabilities of information processing and computation?

From our investigations into the adoption of technology in architecture, we know that to predict the future of architecture is to look at existing innovation already in use elsewhere. The professional vice of late adoption and the trickle down theory remind us that architecture is rife with the process of re-appropriation and re-purposing. Although this is not the sole mode of innovation, it is a significant and important one.

The second method of prediction is to look at technologies proposed in fictional contexts. Culture is a prime motivator in society and it has direct affect on the *desires* and expectations of consumers. Architecture and design are fundamentally linked to films, television, and popular culture in that these media set expectations for consumers. Although fictional, the visuals of fictive contexts provide inspiration for development in real science and engineering, and by trickle down, this has potential for architecture.

The final method that helps with the prediction is to look backwards at the past development, and use the trends and patterns for forward prediction. We are able to do this for technology in architecture, however one needs to look at the development of theory and practice, and specifically we need to know the tools used in both. This analysis clearly cannot account for possible *radical* innovations, but it is one more component in the rhetoric network.

Although these predictive methods are in no way empirical or objective, they are useful in the context of *rhetoric*; as speculative argument for the inclusion of inventions into design. Each process used is a method of *proactive reflection,* offering insight to possibilities of future components and systems. An eye to existing or emerging technologies in other disciplines

---

[7] Flusser, V. (1999)

inform the designer, such that the simplest knowledge of the existence of a new technology, provides potential for future design.

7.1.5. Exponentiation

A bifurcation (of the architectural productivity graph) due to technology has occurred. Innovative use of digital technologies establishes a distinction between "avant-garde" architects and traditional practices. If a paradigm-shift only occurs with mass acceptance of the new paradigm, then this thesis now needs to demonstrate emerging changes that make a technological paradigm-shift in architecture likely. One fundamental way to do this is to expose emerging materials, machines, and techniques that require digital control for their incorporation into architectural design and production. To do this the theory of *exponentiation* will be used to reveal emerging technological trends that promise to impact on architecture.

Because digital systems are fundamentally information systems, this discussion will demonstrate the *exponentiation* of information onto existing technologies in the fields of *matter, energy,* and also *information* itself. Information is conceptually both signal and data, but it should also be perceived as the degree of organization inherent to a system. In systems of low information there is little relationship between constituent parts, in systems of higher *orders* of information there is a greater inter-relation between components. When information is implied onto existing systems, it orders these systems and makes them susceptible to signal or data control. The example of machine tools being converted into CNC or robotic tools is a clear, but highly practical example of this exponentiation, other applications of *information* are much more abstract and conceptual.

7.1.5.1. Matter: Smart Materials

Most building materials used in architectural construction today have changed little in the last century. We are still relying on wood, stone, bricks, concrete, steel, and glass for a large percentage of all construction. Each of these materials has a specific process required to prepare it for use, involving processing and embodied energy that make the material more or less environmentally sustainable.

The basis of a "material" is matter that is shaped with energy and information so as to tune its characteristics for functional use. Current material science has progressed dramatically over the last century; however there has been only (relatively) minor evolution in the interaction between materials and design.

The current interests of material science are focused on new synthetic and composite materials, nano-scale material manipulation, efficient synthetic materials, and production techniques. The concept of "programmable matter" is emerging in advances of 3D-printing technologies, which make it possible to design and then fabricate specific, highly determined and customized composite material formulations.[8]

One significant incoming material innovation are "smart materials"; matter which has inherent capacities for customized response to stimuli. Examples exist in material science and have been employed in other industries of science and engineering. A direct example for architecture is the photo-catalytic Alucobond investigated in the practical work. Other *smart materials* examples include: Piezoelectric materials (producing voltage under stress), Shape memory alloys (pseudo-elastic, controlled and reversibly deformable materials), or Self-healing materials (intrinsic ability to self-repair under stress).

Smart materials can be understood as the conceptual exponentiation of material with the augmentation of a higher *order* of information (and resulting *tropic* control). Such materials can be employed for multiple purposes within a design (as has been demonstrated), and their effective incorporation relies on managing their physical and performative parameters. The behavioural qualities of the material add an order of complexity to the design formulation, but one that can be digitally modelled (design and

[8] Oxman, N. (2010)

behaviour). Through digital simulation, evaluation and digital processing, the multiplicity of characteristics from a smart material can effectively be integrated into a design.

A wide range of smart materials already exists; just as with the proposed Alucobond material, and the existing photo-catalytic concrete, many of these innovations are at the point of emerging into (economically tenable) use in architecture and construction. As more smart materials are available for integration into design, the interactions and potential for complexity increases, and digital modelling for purposes of optimization and balanced efficiency, and the development of composite models will be required.

7.1.5.2. Energy: Control systems

Technologies of energy use in architecture relate either to energy transformation (space conditioning, light, machine work, transport), or to control of these transformations. Advanced context aware *control systems* can be seen as one result of exponentiating information onto energy systems.

Just as neurophysiological and biological theories are used for the control of robotics, similar concepts are being applied to the real-time control of energy systems. The use of increasingly inexpensive sensor systems, now augment the ability to monitor and respond to dynamic conditions, including response to inhabitants behaviours. Control systems use algorithms that are increasingly responsive, that can "learn" and optimize themselves based on patterns of recorded behaviour.

At an infrastructural level, such enhanced control systems have made possible the concept of "Smart Grids": digitally enabled infrastructures that both gather and distribute information about the status of the system. Distributed controllers are enabled to act on this information so as to optimize the performance, reliability, economics, and sustainability of the systems. The biomimetic concept of self-monitoring, controlling, and feedback systems comes from biological organisms, was originally derived for aerospace applications, but has since been used widely in automobiles, factories[iii], and digital hardware such as smart-phones and computers.

As this concept trickles down to architecture it enhances, but also makes more complex the relation of technology with the building itself. As society and governments increasingly regulate energy consumption and environmental impact, the intelligent integration of energy systems in buildings will increasingly become architectural problems. Digital simulation, evaluation, and multi-parametric processing are all tools that can be used rationally for the energy systems alone, or they can be integrated into architectural design to reveal creative design potentials. With broad parametric control over both the spatial atmosphere and the performance efficiency of a space, the design approach changes, and the role and importance of digital tools is enhanced.

7.1.5.3. Information: Artificial Intelligence

The exponentiation of information onto information systems may seem abstract and conceptual, however if it is understood in the same way as adding an intelligent order of "control" onto computation, then the result is "artificial intelligence".

The *science fiction* concept of *Strong AI*; of a fully sentient computer, has not (yet) been achieved, however through advanced programming, cybernetic theory, and whole brain modelling, advances in intelligence processes have been made. The traits that differentiate AI from algorithmic computation include: reasoning, strategizing, learning, and perception, and the ability to coordinate and integrate these skills towards a common goal.

The current status of computer intelligence is at the level of responsive machines: able to discern patterns, apply heuristics, and learn generalities of a situation. This level of information processing is however still of great interest within the architectural realm.

The addition of learning, pattern recognition, and heuristics to design algorithms changes the relationship of the designer and the tool. The use of such "smart" design tools, might reinforce rational decisions in a design, but with differentiated input might also support greater creativity and abstraction in a design. The design product could become embedded with knowledge and past experience as recorded and interpreted by the "smart" tool.

In the 1992 book "*The Age of Intelligent Machines*" futurist Ray Kurzweil's analyses the progression of computation power compared to the neural processing power of the human brain, and argues there is no fundamental technical limitation to the concept of AI. "*Though not yet up to human standards, pattern-recognition technology is sufficiently advanced to perform a wide variety of practical tasks. It is difficult to estimate when these capabilities will reach human levels, but there does not appear to be any fundamental barrier to achieving such levels*."[9]

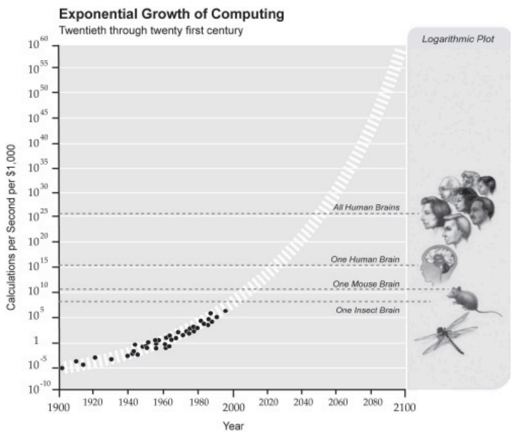


Fig.7.1.5. Computational processing capabilities: technology compared to biology (graph 1998). (source: R. Kurzweil: www.singularity.com)

If AI were to be applied to the concept of the digital chain, the greater overall system would then have a learned and cognitive functionality; supporting the individual tasks, but also managing the relationships and feedback between tasks. Because the entire process would have its own "environment" *third order cybernetic* feedback (double loop learning) could potentially affect (and theoretically enhance) autonomous design decisions throughout the process.

Although, this final example of *exponentiation* seems the most futurist, fantastical, and abstract, the reality is that this field of research has been in development since the 1950's.[iv] The advancement of (semi) intelligent digital design based on algorithmic methods has recently seen extensive progress primarily due to the greatly expanded access to scripted design made possible by the creation of easy scripting languages and interactive interfaces such as Grasshopper. As the use of such tools increases, so too does the complexity of their application. Creative designers and researchers may yet find ways of bringing "smart design" to digital production.

7.1.6. Evolving technology

The concept of *exponentiation* has a direct analogy to the understanding of the *orders* of cybernetic feedback. By extrapolating (or expanding) the understanding of a phenomenon, in the context and frame of reference of a second one, it is possible to understand the relationships between the current state of technology, and a range of potential emerging states.

The preceding examples demonstrate how an understanding of *information* (and how it relates to computation and the transformation of signal as data) can be used to predict emergent technologies that might affect design and production. In the examples given information was chose as the exponentiator, given the thesis's focus on digital and intellectual technologies; however the same processes are also applicable to *matter* and *energy*:

---

[9] Kurzweil, R. (1992): 459.

- Energy exponentiation of matter (tools) produces improved work efficiency of common tools, and advances of strength in heavy tools.
- Energy exponentiation of information results in advances in communications, signals, and processing capability.
- Matter exponentiation of energy can be seen in advancements of batteries, capacitors, and energy storage.
- Matter exponentiation of information is understood as improvements of memory, circuits, and other electronics or information recording media.

Each transformation requires peripheral innovations, typically in areas of design, production, and manufacturing, which in turn are fodder for new innovations of design and construction. As knowledge and technologies "trickle down", their implementation into architecture is dependent on designers who have intelligence and skills, but more importantly; foresight.

As the technological context of tools and processes evolves, so too will the requirement of architects to adapt and engage such innovations.

The motivations to engage with emerging technologies are many (including substantially: environmental, economic, and social change…), however care is also needed to ensure that the resulting design continues to be appropriate, and not technocratically superficial. An augmented knowledge of technologies, including both the broader contextual implications, as well as alternatives and emerging trends, allows designers to make informed design decisions, which should help ensure high quality of design. *Exponentiation*, as a concept is a speculative method to inform the practitioner, but it also continuously returns them to basic principles and the root concepts of phenomena, and this promotes fundamental and honest reflection.

7.2. Evolution of architecture

> *"Client expectations for all products have been dramatically reshaped in the last decade by increasingly positive experiences with technology enabled customization. Parametric design is ideally suited to the repetition and non-standard processes of rapid fabrication. As such, parametric design skills need to be among the dozen or so capabilities that define the digital toolboxes of forward-looking architects."*[10]

Have digital technologies created new epistemology of architecture? This question was discussed in each of the thesis investigations, but responses were divided. This disjoint may be attributed more of a lack of historical knowledge, than a critical position on contemporary technology. Current practitioners (and students) are increasingly exposed to vast sources of information about technology and architecture, with most of it depicting "the now" or "the future". As such, understandable (but unfortunate) allowances need to be made for neglecting the history of technological architecture.

Vanguard architects continue to investigate parametric and digitally mediated design. This work is typically *exploratory* in nature, with focus on the technology itself, rather than on goal states of functional or architectural purpose. With such emphasis on formal geometric complexity, these investigations are often criticized for superficiality and a lacking in theoretical or historical reflection.

7.2.1. Historic algorithmic design

Participants in this thesis cited scripting, and specifically parametric design as the most significant innovation within the digital chain.[11] The idea that parametric design is "new", however, is profoundly false. Parametric design and conceptualizations of architecture as "systems" are evident throughout history.

---

[10] From: Celento, D. (2007): p.7

[11] See: Section 11: Findings

In current architecture, the output of scripting is often associated with expressive "freeform" geometries; however, such form and parametrics are not exclusive to each other. Associative (parametric) design has been the mainstay of other industries for decades, where such design techniques typically have no "stylistic" role. In engineering software parametric design is the established norm.[v] Object oriented methods and geometrical associativity are typically used for efficient project management, model refinements, and overall optimization. What is interesting for this thesis is that the concept of parametric association in design actually traces much of its history to precedents within architecture.

Methods for logical conception of complex form emerged in the physical parametric investigations undertaken by architects and engineers alike: The early structural investigations of Vladmir Shukhov; Gaudí's hanging model of the Colonia Güell Chapel; The compressive shell structures of Candela and Torroja; the soap films of Frei Otto, the hanging fabric shell models of Heinz Isler, and the geodesic domes of Buckminster Fuller, are all examples of physical parametric models. The resulting forms were all determined using scale models combined with a scientific approach to determination of the systems.

In each case the complex forms were "generated" by the interaction of materiality, design interventions (constraint points, connections, and forming) and the counteracting real world physics of tension and gravity. The models were intelligently devised as both explicit design models and structural behaviour models, and the resulting logical (but also beautiful) formations revealed the free flow of forces within material leading to a broader engineering comprehension of complex form. These models were the prototypes for complex full-scale constructions, all accomplished without computers. This physical modelling process is the precedent for contemporary parametric programming and structural evaluation.

This retrospect on structure is but one example, to demonstrate that the longstanding concept of parametric programming (and its use in architecture) is in no way radical, but rather the digital version is another iterative evolution and digitization of historical practice.

7.2.2. Process chain

The process chain in architecture is also not a new concept. Just as CAD evolved from drawing, the *digital chain* is the digitization of the traditional processes used in the overall development of a project. For all the "links" in the digital chain there have been previous analogues of method or process, (with exceptions, which we will discuss momentarily).

There are two significant changes brought forth by the digital chain, but both apply not to the conception of method, but rather to its execution: The first is "desktop" access to all of the processes, the second is the relative ease and speed of transmission of results from one link to the next, (and resultantly the appearance of digital continuity). These advancements do change the approach to design; in the same way that a craftsman's approach is influenced and motivated by access to particular tools.

The existence of these digital tools, their increasing use with avant-garde architects, and their gradual adoption in practice, all support the statement that a bifurcation of the architectural process has occurred. However, as has been previously stated, a paradigm-shift (the determining criteria for this thesis) is defined by mass acceptance of a radical innovation, and this is clearly not the case; the digital chain alone is not radical and it has yet still be to wholeheartedly adopted in practice.

7.2.3. Radical simulation

The one (noted) digital capability that is a radical innovation is the simulation of complex dynamic behaviour, and the use of the results for prediction within architecture. The calculation of fast but highly complex speculative models of *behaviour* is unprecedented in the *digital chain*.

Digital models have the inherent quality that they are simultaneously the representation and the empirical definition of a design. As more detail and associative information is imbued into a model it becomes more useful for simulation and evaluation. As models become higher *order* digital models (as the data has its own internal complexity), they render the processes of analogue simulation obsolete.

Simulations (from basic visual rendering to complex analytical modelling) rely on two interacting models: a *design model*, containing all pertinent physical and contextual data; and a *behavioural model*. Behaviour models are conceptual encodings of all potential dynamic interactions for the time and space of the simulation. The precision of the models and algorithms determine the simulation tolerances, and the bounds of these processes are both epistemological (clear knowledge and ability to model the situation) and logistical (having enough processing power to deal with magnitudes of computation).

However, it is not the ability to *simulate* that is in itself radical, but rather it is the potential for *orders* of complexity and potential for emergence within behavioural models that makes this process novel.

7.2.4. Autonomous agents

Complexity of interaction typically occurs due to *emergent* behaviour; the logical but amplifying actions of relatively simple rule sets. This concept may be manifested in design models through the use of programmed *autonomous agents*; encoded digital entities that "populate" a model. Each *agent* has its own set of simple behaviours, which are both goal seeking and interactive.[vi] Complex patterns emerge through interaction with the model, behavioural stimuli, and other agents. This ability to simulate *emergent* scenarios has no analogue or historical counterpart.

This simulation data, when fed-back to the generative processes of architectural design can be used to refine and optimize geometry based on such highly complex behaviours. However, the value of theses processes is not restricted to the geometry of a project. For advanced complex simulation processes, such as acoustics, crowd movement, and environmental simulation, prediction has potential to assist with the psychological, sociological, and mechanical refinement of architectural design.

7.2.5. Performativity

Simulation is conventionally associated with spatial character (perception of the space, through renderings, animations, and other visualizations), however performance and regulatory evaluations of a design are increasingly influencing digital design methods. The importance of energy, environmental and process evaluations for building projects will only increase in the future.

The solar simulations and feedback of the Alucobond structures occurred at a relatively simple level. The simulations from the FLOW project were far more dynamic and complex, but the data was interpreted manually. The integration of such technology is still relatively complicated and requires experience, skills, and adequate computing resources; however costs and intricacy continue to decrease, and the associated skills of creating the designs and behaviour models are becoming accessible. "Cloud" based services now enable "remote processing" of computationally intensive processes, which allows for "almost real time" design analysis. Simulation technology is still underutilized, but with the increases in speed an reductions of requirements for hardware there is better potential for its increased use. The inclusion of simulation in the *digital chain* is clearly desirable, but it is also still an expertise rather than a normal architectural tool.

7.2.6. Designing design

The act of design is a series of conscious decisions, which enact strategies that are tested and executed following predetermined sets of constraints or rules.

Programming is the explicit encoding of a set of logical operations and constraints that provide a result when fed with input parameters.

The processes are ultimately analogous in that they do not result in a goal, but rather they are the process of making information and instructions to define the resultant. The architect/programmer is the designer and actor in this process; who defines the components, relations, and hierarchies of the system, be it a building design or a software program.

Specific design strategies are common to both architecture and programming, and both designers and programmer engage in *reflective practice* as they develop their projects. "*Evolutionary software development approaches including agile methods draw their strength from the possibility of continuous reflection. One of the key principle in the agile manifesto is, "at regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behaviour accordingly.*"[vii] As programming is required to become more innovative and efficient to deal with computational complexity, it seems natural for the discipline to look towards creative design patterns and methods.

As the tools that architects are using become increasingly embedded in the digital realm it also seems logical that methods would emulate programming. However as this research progressed, the available technologies changed.

With the development and popularization of "visual scripting" methods (Generative Components, Grasshopper, Revit…) the need for architects to interact with the explicit syntactical methods of programming and scripting were reduced. The result of this is that the methods of parametric and generative design are still being engaged for project work, but there is a technological "buffer of pre-defined programming tools" between the designer and the basic principles of logic and methods. In short, the *visual scripting* tools short-circuit the need for explicit understanding of the digital processes and their use in developing new theory or abstract understandings.

Visual scripting facilitates the engagement of logical methods and associative design, a significant advantage for teaching and initial parametric design work. These platforms change the learning curve for digital design, but it also places new barriers. Tools in such *visual scripting* platforms are flexible within limits; in order to go beyond, the designer must engage in programming and scripting of the tools. At the advanced level the engagement of "first principles" still requires syntactical coding.

This thesis began by identifying the fact that architects are reluctant to adopt tools that inhibit creative abilities. Digital processes cannot replace innovation, however innovative application of digital tools can improve productivity and the ability to react to the more demanding "real world" requirement for efficiency. It is a concern that such a situation may lead to a reduction of capability rather than an increase in innovation.

The architect-engineers highlighted at the beginning of this discussion were able to make innovative geometrical and structural discoveries by engaging the *basic principles* of their craft. The cross product of intellectual understanding and physical experimentation created a new understanding that allowed for the efficient making of freeform and unconventional structures. If this tradition of radical invention is to continue then it needs to be understood that the programmer and designer are not independent, but rather they are one and the same.

7.2.7. Parametricism

Several outspoken architectural practitioners and theorists have inconsistently branded freeform geometries as "parametric design"; however this form of design is neither a "*new mature style*",[12] nor is it "*a radical innovation and a paradigm-shift within architecture*."[13]

Architect Patrick Schumacher in his assertions of "*Parametricism*" as a new 'style' neglects the importance of the link between style and culture. Although 'style' is 'rooted in' technique it cannot be reduced and defined by technique alone. As we have discussed parametrics are a method for integration and reflection of external data. A style, parametric or not, is still

[12] Schumacher, P. (2008)
[13] Lynn, G. (1998)

inherently the resultant of the design decisions made by the designer, or in this case the programmer. An architecture may be parametric and yet may still engage local design values and contextual influences to be culturally sensitive. Freeform architectures by contrast may be justified with performative calculations, but they often seem distinctly abstract, difficult to interpret, contextually insensitive, and disconnected from locality.

The re-engagement of historically developed parametric methods into design changes architecture thinking, but it also reveals a banal and somewhat lazy digital intelligence[14]. Embedding information into models increases their "validation value" before construction, but it does not ensure design excellence. Digital modelling and behavioural evaluation software creates a sense of confidence in the value of a design, but it also potentially alienates the designer from "thinking" through the physical analogues. Creative intelligence and physical construction knowledge is required as a counterpoint to balance these convincing and strong digital justifications.

As our "digital intelligence" evolves, the concepts of associativity, logical links and design extrapolations may evolve in unforeseen ways; however, it will not be mindless digital combination and permutations of method that will lead to innovation, but rather it will be creativity, intelligence and an understanding of the basic principles of architecture and physicality that will reveal new potential.

A *paradigm-shift* is fundamentally defined by mass acceptance. Within normal architectural practice, the current implementation of digital technologies does not satisfy these criteria. The use of digital tools has not fundamentally changed the *theoria* nor the *praxis* of architecture: the very definition provided by *Vitruvius*. For architects to understand their own profession it is imperative that they situate innovations within the architectural discourse of practice, theory and history; …given that what is considered "avant-garde" today, is already the preamble to future architectural history.

7.3. Tool or Partner

Since the advent of computational graphics and geometry programs, architects and designers have increasingly been impressed with the possibilities of digital tools, but also wary of changes brought forth and also imposed by the digital medium.

The technology of the "autonomous machine" has a well-documented history of changing established practices. In industry it replaced workers; radically in the industrial revolution, then progressively throughout the industrial and electronic evolutions of the last century.

The contemporary version of the industry changing machine is an *information machine*; the computer, and its incorporation into design practice (through the use of CAD software) has already (essentially) eliminated the position of the architectural draughtsman. As digital tools and processes increase in sophistication, architects seem to be wary of their own future given their on-going turbulent relation with machines. This unease may be one factor contributing to the situation that architecture, as a professional discipline and an intellectual pursuit, is also a notorious late adopter of technology.[viii]

7.3.1. Risk assessment

There may be many reasons why a transition of working method is difficult for designers and artists, but psychology and natural risk aversion is a primary driver[15]. This apprehension, however, is not universal; it is typically associated with established practitioners, where new technologies pose a risk to the established and predictable methods.

Younger designers now entering the profession (who have grown up in the "digital age") have a different experience, understanding and skill base. Their facility with computer interfaces,

---

[14] Paraphrased from: Meredith, M. (2009)

[15] From: Argyris and Schoen, (1978).

data manipulation, and the pervasiveness of "gadgets" in other facets of their life, all ensure that the digital medium is intuitive to their methods of working. New practitioners have less commitment and investment in established methods (and equipment), and thusly they may appreciate a flexibility found in abandoning older methods, and in building new ones.[16]

However there is one common agreement between old and young: the use of the computer in practice does change the nature and methods of design. As methods change so to do the intellectual conceptions, leading to new understanding and theory of architecture.

"Both non-users and users agree that the effect computers will have on design whether desirable or not, will be significant, profound, and far-reaching." [17]

7.3.2. Computer as tool

Our current phase of computational machines is such that they are obedient servants that lack even enough *intelligence* to question our demands of them. However, even in its most rudimentary application, the computer is more than a simple tool. It is a tool that makes both conceptual and procedural demands of the user, but because the tool itself also provides informational feedback, its influence is complex and dynamic.

Despite the digital enhancements to working capability, the standard for creative design practice remain conceptually on visual cognition the traditions (if not media) of sketching, drawing, modelling, and eventual documentation. Digital tools impose a working manner that does not intuitively follow these norms, thereby enacting a permanent intellectual state of "*work-around*". Although there have been exceptional advances in CAD software design, the digital medium still requires the user to confront and conform to its structures.

Although other tools and mediums also impose constraints, the cumulative abstract, ethereal, and objectively logical constraints of the digital medium often confound the abilities of a designer to achieve their "perfect" envisioned design objective[ix]. Ensuing compromises can be a source of frustration and cynicism, further alienating the designer from the tool.

So, what should be the exact scope of the computer's involvement with architectural design? Architectural practitioners fall into a wide range of approaches to using the computer in practice, but at the extremes of the range, there are two fundamental categories.

For most architects, the computer is an advanced tool running commercial software that enables design practice with enhanced degrees of drawing and data management. For these designers, the computer does affect the architecture that they are able to produce, but the conception and design decisions still originate from "within" the designer.[x]

The alternate set of practitioners delve into the workings of the toolset, they engage with the programming of their software, with the functioning of the computer at its internal level, and make creative use of computation within their design methodology. It is this group that also takes engagement with the digital chain, due partially to their conceptual understanding of data structures and the relations between different links. The investigative and experimental approaches can be seen to permeate both the design and production of projects, and to produce truly novel and innovative results.

Media theorist, Neil Postman describes three stages of how a culture deals with technology: The first is *tool-using* culture, where technical improvements are limited to the uses at hand. This differs from the *technocracy*, where the tools "play a central role in the thought world of the culture" and *technopoly*, where tools become the culture.[18]

Postman's theories were developed as both a categorization, but also as a vague warning. He was alarmist in his concerns for information and how it is validated. Postman compares the

[16] From: Argyris and Schon, (1978).

[17] Terzidis, K. (2006) *"Algorithmic Architecture"*: P.25

[18] From: Postman, N. (1992): p.69

doctrine of Middle Age religion, to that of contemporary science, where there continues to be a lack of critical reflection on what is deemed "truth".

In conceiving the computer (or in general technology) as a tool, the architect subscribes to the notion that we are a tool-using culture. However to differentiate the stages, the architect must also have an informed ability for critical thinking about both technology and design that extends to their working medium. To defend the shift from *technocracy* into *technopoly* the designer needs critical insight to all the functioning *orders* of influence.

In our contemporary society some aspects of life are clearly already *technopolistic* (ex: communications), whereas the current state of architecture can be seen as ranging from *tool-using* to *technocratic*. If there is to be a paradigm-shift to a *technopolistic* state, then how does the role of the computer change, so that it is participant in the culture?

7.3.3. Computer as Designer

If one regards design as a creative mental process, then the computer as an "augmentation apparatus" for this mental process clearly fits the definition of a tool. The tool plays a supportive role to the intellectual processes, but does not override or circumvent them; the tool supports the creative authorship of the designer. However, what if a tool is also capable of creativity outside of the designer's control? This situation would confound the perception of the tool, and its role within the design process.

In the book *Algorithmic Architecture,* Professor Kostas Terzidis proposes that this is not a future condition dependant on Artificial Intelligence, but rather it is a present occurrence. Prof Terzidis proposes that through the development of higher orders of cybernetic and algorithmic feedback, authorship in design may already be in question.

Algorithmic design provides potential for a new *order* of design, in that the algorithm can be programmed to output *geometry*, but it may also be programmed to output *code* that defines geometry. Although this differentiation may seem semantic, it is important to understand the output of code that defines geometry may, in itself, be parametric. This is an example of information *exponentiation* of output. If an algorithm is formulated and executed such that it alters its own code (*second order cybernetics*), the ensuing change produces new rules and behaviour. This condition run iteratively is the basis for a second order feedback loop, and Terzidis gives this second design output method the name: "meta-algorithmics".

In scripted design there is potential for situations where computed results do not match the design intention. In situations of poorly conceived logic, faults of algorithmic formulation, misunderstanding of behaviours at limits, or simply not perceiving *emergent* behaviours of combined rules; in such cases the results may be fundamentally "correct and appropriate" but may also be different than the intention of the designer.

> *"It may be assumed that meta-algorithmics, the creation of algorithms that generate other algorithms, is a human creation. A human programmer must have composed the first algorithm that, in turn, generates new algorithms, and as such the initial programmer must be in control of the original idea. However, this is not necessarily true. Unlike humanly conceived ideas, where the author is the intellectual owner of the idea, algorithms are processes that define, describe, and implement a series of actions that in turn produce other actions. During the transfer of actions it is possible for a discrepancy to occur between the original intention and the actual result. If that happens then, by definition, the author of the algorithm is not in control of, and therefore does not own intellectually from that point on, the resulting process."*[19]

Confounding this further, algorithms may be devised without predetermined goals or intentions, where the only explicit rules are the creation of functioning algorithmic results

---

[19] Terzidis, K. (2006) "Algorithmic Architecture": P.20

(working code) and cybernetic feedback (progressive change). Such algorithms are characterized by unpredictable behaviour, as there is no explicit design intention.

> *"This structural behaviour resembles in many ways Dadaist poetry, or Markov processes. In those cases, an algorithm functions as a string rewriting system that uses grammar-like rules to operate on strings of symbols in order to generate new strings of text. While the syntax of the resulting text may be consistent with the grammatical rules, the meaning of the resulting text is not necessarily associated semantically with the intentions of the original code. For instance, the introduction of randomness in the arrangement of text can produce results that are unpredictable, but also accidentally meaningful. Unpredictability is, by definition, a disassociation of intention. But unlike chaos, a random rearrangement of elements within a rule-based system produces effects that, although unpredictable, are intrinsically connected through the rules that govern that system."*[20]

If computational processes can be conceived as being inherently "creative" then in the absence of human design authorship (as a designer neither directly conceived, nor controlled the development), credit is appropriately attributed to the computer. This situation, although highly specific, is a demonstration of how computers with conceptual algorithms may shift the conceptual role of technology within architectural design.

7.3.4. Critical oversight

The increasing use of digital technology in architectural design creates increasing potential of un-authored *emergence* of algorithmic creativity. This possibility might actually validate some of the professional fear of computers replacing designers. However, before designers despair, there are some additional considerations to review.

Previously in this thesis, two additional archetypes of design were validated; "*Design as Rhetoric*", and "*Design as Reflective Practice*". In both cases the methodologies function through the intrinsic act of subjective criticism. This free-association of ideas and the freely associative ability to criticize them is still fundamentally lacking from algorithmic process.

> *"(A designers) … virtuosity lies in his ability to string out design webs of great complexity. But even he cannot hold in mind an indefinitely expanding web. At some point he must move from a "what if?" to a decision, which then becomes a design node with binding implications for further moves. Thus there is a continually evolving system of implications which the designers reflects-in-action."*[21]

The creative ability to intermingle conceptually desperate ideas, so as to imbue a design with an internal tension, playfulness, or other emotionally engaging virtue still defies explicit instruction or analytic definition. As with the development of *the problematic,* such subjective characteristics are developed through refinement and process; the working of the problem intensifies its qualities, not an initial idea. In *reflective practice* design is defined as "process" and for it to function the procedure must be open to changes of interpretation throughout execution; the result is a "product of the journey, not the destination."[xi]

Radical innovation, by definition, can only occur when a change in fundamental understanding of a situation occurs. To make such a change there needs to be a "*suspension of disbelief,*"[xii] the hope that through exploration new possibilities will emerge. Through search comes insight and the knowledge for criticism and reflection, and with this confidence comes the courage to ask: "*what if?..*" With this question, a designer engages the problem with their *gestalt perception,* and this differentiates their inquiry and solution process from any predefined logic or explicit programming.

---

[20] Terzidis, K. (2006) "Algorithmic Architecture": p.21

[21] Schoen, D. (1982): p.100

The validation of design using rhetoric and argument requires an acknowledgement of *logos, pathos, and ethos.* Whereas logos is clearly in the favour of digital tools, both *pathos* and *ethos* are subject to the presentation and justification of the design by its author. At this point, the potential creative role of the algorithm becomes destabilized. If the evaluation criteria are no longer fundamental rationality, but are rather emotional and subjective, then the human (and irrational) designer will always prevail.

But critical reflection itself is also most effective when unconstrained. Schoen describes this as "shifts in stance": "As a designer spins our his web of moves, his stance towards the design situation undergoes a series of changes" The language of reflection changes- speaks of what "can or might happen" rather than what "must or should" happen."[22]

These subjective and speculative moves mostly defy explicit programming and logic, and designers may argue as a result that authorship can only be credited to an "agent" that possesses awareness of its ownership. So if the computer can be a "designer", but cannot be an author capable of defending design moves, then what role, evolved beyond tool, dose it play?

7.3.5. Computer as Partner

> *"We shouldn't consider the computer as an extension of the mind, but rather as a partner in the design process with fundamentally different aptitudes and ways to reason. The computer is the "other" of the human mind, not its mirror."*[23]

In the "architecture machine," Nicolas Negroponte describes the early teaching work and the need to reinforce the design relationship between the (large mainframe) computer and the students. The program was devised to use language methods to monitor the users work. After observing a user's behaviour, the machine could reinforce a dialogue by using predictive models. The role of the machine was conceived to work as a close and wise friend assisting in the design process, using "mutual persuasion and compromise to bring about ideas."[24]

At its introduction into architecture, the computer and CAD software was a tool to augment workflow. As the capabilities of the various digital machines became known (and as skills developed) the computer slowly overtook and replaced human roles, first the draughtsman, then the print maker, and now increasingly, the model maker. The current status of the tool is that of *assistant* to the architect, a hybrid tool, managing trivial tasks and augmenting decision-making capabilities; however, as the technology evolves so too will its role.

> *"The strengths of today's machine intelligence are quite different from those of human intelligence and in many ways complement it."*[25]

Although our current archetype of design resists the concept of an "artificial intelligence" based designer, it does fully support collaborative partnerships within project teams made up of experts from the disciplines of engineering and construction. If digital tools are currently seen as assistants in the different facets of the digital chain, and if each digital process has (at minimum) some capacity for creative output, then should the computer not be seen as an overall "assisting team" in the project?

A designer's work at the management level of a project, is the organization, prioritization, and combining of the different components and stages that define the overall job. Each problem, process, and phase in the project chain is controlled and devised by the designer, and engineer, a specialist, or another agent or member of the design team. Accountability for process, method, choice of tools, workers, and also the results, is the responsibility of the team member. They are tasked with the work and with returning a valid set of results that meet expectations and can be integrated into the whole of the project.

---

[22] Schoen (1982): p.101

[23] Antoine Picon, from the forward to: Terzidis, K. (2006) "Algorithmic Architecture": p.viii

[24] Negroponte, N. (1970) "Architecture Machine": p.13

[25] Kurzweil, R. (1992):p.459

Can the same not be said of the digital tools used in the digital chain?

When a human designer engages the digital chain, they are engaging with a list of digital assistants who aid in the tasks associated with each link. As the digital associativity expands along the chain (or across the network) the digital connections and parametric associations between each of the "assistants" grow; and the conceptual boundary between each blurs and the assistants will form a singular multi-modal programme.

Furthermore, if the futurists are correct, and the pattern recognition, interpretation, and processing capabilities of the computer evolve to the point where they rival human capability, then they will have equally enhanced their already fast and precise capabilities of logic and mathematics. In this way, the computer will never be the "equal" of a designer, as the sensibilities will not be aligned. The role of the computer will always compliment the designer, rather than replace him, and in this way the *assistance* should be understood as a partnership, and not a subservience role of master and accomplice.

If design is entrenched in the *rhetorical* method and the search for a collaborative and consensual *design truth*; then the approach to the computer as a "partner" rather than as a tool is complementary. The *logos* and *ethos* of computational design adds to the credibility of the *design team*, but it cannot replace the required *pathos* of the designer or architect.

This metamorphosis is (for now) still conceptual, however with the current advances in computational power, and biological and neurological intelligence models being integrated into control programming, there is significant possibilities that the individual assistants of the *digital chain* will mutate into digital design advisors, and eventually even feedback "partners".

The digital chain promotes a partnership where the digital agent deals with the objective, explicit, and analytic tasks of process, and where the designer trusts and uses this complex feedback. By engaging computers as reliable tem members, who are active across the overall process, the partnership leaves room for the designer to concentrate on abstract creativity.

7.4. Outlook

"Technology and architecture are in a persistent state of change." This statement has been repeated a number of times in this text. The future outlook for this thesis work, takes its cue from the fact that this document is an analysis of the *current* state of both architecture and technology, and as both systems evolve there will continue to be need to evaluate them.

7.4.1. Environmental performativity

The clearly most pressing issue in the development of contemporary architecture is the need to address environmental and performative issues in buildings, urbanity, and all aspects of civilization. Both technology, and novel conceptual approaches to architecture can contribute to this *wicked problem*. The application of advancing simulation and evaluation technology, and the ability to feed this solution data back into design presents an analytical tool set to compliment the creativity of architects and designers.

By increasing the *orders* and the overlay of systems, the simulations will continue to be increasingly complex, however the ability to create fundamentally responsive design will improve. Such tools are (currently) not intuitive to architects, and as such one of the main requirements for effective implementation is to improve their clarity, usefulness, and immediacy of design feedback. With advanced toolsets designers should be able to engage more effectively with the science and analytics, without loosing the abilities to author highly subjective, and creative urban interventions.

Future research in this area would focus on advanced digital simulation of design, feedback of performance factors, and their integration into the process of architectural projects. The functional goal would be an increase in all facets of efficiency across the digital chain, but the overall meta-goal, should remain to improve the quality, and creativity of authorship in architecture.

7.4.2. Material transformation

The most rationally innovative issue addressed in the thesis is the issue of material transformation. Current scientific progress is clearly making significant advances in materials that are applicable to architecture. The introduction of genuinely new materials to architecture holds great promise for the creation of novel and interesting design; the application of reformulated and "evolved" materials has potential to make the public reconsider their understanding and pre-conceived notions of existing materials; and the development of new biomimetic materials offer performance, responsiveness, and adaptability potential that make possible fundamentally new concepts of dynamic and truly "organic " architecture.

The "trickle down" theory continues to make architecture a discipline of adoption and repurposing, however advancements in production technologies are transforming the scale of "integrated manufacturing", and this will further enable the architect to work as a material designer. Digital design and digital fabrication machines have allowed architects to return to their original role as craftsmen, undertaking both design and production. As the precision of 3D printing technologies evolve, and as new printable materials are introduced; the designers role in the creation of performative customized composite materials becomes possible.

Future research in this area would investigate material innovation with specific focus on responsive materials and processes that engage environmental and ecological performance. Materials research should intersect with all of the links of the digital chain to show how system-wide implementation could improve the resulting architecture.

Fig. 7.4.2. SPUN bench - Mathias Bengtsson: Spun carbon fibre structure as an extreme lightweight structural free-form tube. The entire structure weighs less than 40kg.

7.4.3. Intelligent architecture

The final proposal for future research is to truly engage the idea of the computer as a partner. Currently we are in a period of change in how we engage with computation. New devices are using touch, spoken word, and free-3D gestures to control digital programming. Concurrently the processing power of computers continues to increase according to Moore's Law, and the interconnectedness of cloud computing and digital communications is fully implemented. These hardware, and technological developments will surely change the way that the architect interacts with their digital "partner".

Future investigations should look at changing the interface of CAD systems, and incorporating "learning" algorithms as a form of pseudo-AI so as to improve the interaction between architect and their working partner. Although this final outlook for the integration of next-level technology may sound futuristic, we already have voice controlled mobile phones, touch based tablets, and gesture controlled video games. With the ever-increasing access to computing power and ubiquitous devices, these advancements are technologically possible, and may radically change the working methods of architectural design. Given the knowledge of plasticity of tools, and the effects that they have on our intellectual approach to a task, an investigation into such new methodologies would also be of interest to *theoria* and *praxis*.

7.4.4. Future outlook

"Architects drew what they could build, and they built what they could draw".[26]

The methods of drawing have changed. The concept of digital space has broken through the barriers of 2D and even 3D, and models now exist in temporal space that includes time-based issues of performance, behaviour, process, and lifecycle. Digital tools have proven themselves as a *disruptive technology* to the profession of architecture, the bifurcations of the technological productivity graph are clear. However for the profession to fundamentally declare a paradigm-shift, the issues of performance, materiality, and technological epistemology still need to be addressed.

The thesis began by asking what factors can be manipulated to "foster creative innovation in a technologically mediated architectural practice." In conclusion it is not the technology itself that needs to be manipulated, but rather it is our approach, understanding, and acceptance of technology that will enable a paradigm-shift to occur.

Endnotes:

[i] For a full investigative depiction see Apendix: Industrial Revolution

[ii] Paulinyi demonstrated that material-forming processes were the common denominator of technological development. Paulinyi, A. (1986) "Revolution and Technology."

[iii] Manufacturing Operations Management Systems (MOMs)

[iv] ...beginning with the work of Alan Turing, and progressing with Marvin Minsky, and then on to architects Cedric Price, Gordon Pask, and later, John Gero.

[v] Ex: Solidworks, Catia, TOPsolid

[vi] An agent may represent a person with determined behaviour characteristics; but the concept should also be understood to be able to represent any free entity with behavioural characteristics within a system. Ex: a particle of smoke, a virus, a shipping truck, or a data packet in transmission.

[vii] Hazzan, O. and Tomayko, J., (2005) Reflection and abstraction processes in the learning of the human aspects of Software Engineering, in: IEEE Computer, pp. 39-45, June 2005.

[viii] There are also clearly other significant reasons; including the traditional master-apprentice system of architectural practice, the economics of small offices, costs of learning and implementing technology, and the requirements of working with other professionals and regulatory structures.

[ix] This was repeatedly mentioned in participant feedback, during the practical investigations.

[x] Note: Despite claims to the contrary, most "digital architects" from the 1990's and early 200's fall into this category – see: Cahola Schmal, P. (ed) (1998)"*Digital Real: Blobmeisters, first built projects*": p.12

[xi] To paraphrase the American philosopher Ralph Waldo Emerson (...and the rock band Aerosmith)

[xii] This concept of "suspension of disbelief" is fundamental to both philosophies of "fantasy" and creative design. Expounded by the literary philosopher Tvetan Todorov, the concept was discussed at length by this author in the paper: Loveridge, R. (2010). "Fantastic Form: Digital Design as Fiction and Fact".

[26] Professor Bill Mitchell, from presentation at the *Non*-Standard A*rchitecture* Conference, MIT, 2004.

8. Dénouement

8.1. Athena as myth

> *"We will say no more about this, for we both know craftiness upon occasion. You are the best counsellor and orator among all humankind, while I for diplomacy and crafty ways have fame among the gods."*

- Athena to Odysseus: The Odyssey[i]

Athena, the goddess of crafts and skills; is in many ways the poetic counterpart to Hephaestus, the god of technology; both in being harbingers of arts, and in the violence of their births.

Despite dire prophecy and warning; Zeus the king of the gods lies with Metis, the goddess of wisdom. Immediately afterwards, knowing that wise children are destined to be born from Metis, and fearing that her offspring will have power over even him; Zeus acts with impudence and "*swallowed her down all of a sudden, and put her away inside his belly,*"[ii] however this action is too late, for Metis has already conceived.

Eventually Zeus experiences an enormous headache, and Prometheus is called to cleave Zeus's head open with an axe. From the opening emerges Athena, fully grown and fully armed for battle. …Hera, the wife of Zeus, is so enraged at him for having produced a child that she jealously and vengefully conceives and bears Hephaestus by herself.

Despite her violent arrival, Athena becomes a favourite daughter of Zeus, however it also becomes clear that the prophecy is correct; Athena is credited with "*inventions that are not of the kind which men make by chance or accident, but such as require thought and meditation.*"[iii]

Worshipped for her wisdom, inspiration, and strength, Athena is said to have brought to man the concepts of civilization, mathematics, order, and strategy, and insomuch she is conferred as goddess of creativity, architecture and patron of universities.[iv]

Athena and Hephaestus were the gods of useful and elegant arts, responsible for bringing the wisdom, inspiration, and skills of design and making to mortal artists.

> *"I sing of Athene, the glorious goddess, bright-eyed, inventive, unbending of heart, and courageous saviour of cities. From his awful head wise Zeus himself bare her arrayed in arms of flashing gold, and awe seized all the gods as they gazed. And wise Zeus was glad."*

- Homeric Hymn16 to Pallas Athena

8.1. Athena as inspiration

Just as Zeus could not contain the arrival of Athena, the profession of architecture has little control over contemporary digital technologies. Any invention can be understood as a point of *conception;* and as an innovation gestates, is tested, and becomes disseminated, it affects the primary users and their perception of their work and design. Whether such an innovation is a *disruptive technology* and will invoke a *bifurcation* in the productivity graph depends on its qualities and merits, but also on its perception of overall acceptance. In this age of mass digital communication the potential for wide propagation is great, and the speed of adoption of technologies is well established, and increasing. Adoption and acceptance of effective and appropriate innovations occur quickly, and they often have lasting, and *disruptive* effects on both the working techniques and the organization of the profession.

When innovations do become widespread they are now popularized and evaluated in a much larger, technologically mediated (internet) world-view. This evolving situation creates a condition where two distinct paradigms can exist simultaneously: the globalized paradigms of digital communications and information; and the localized paradigms of real-physical activity. One paradigm that is applicable in technological "digital space", and the other one that is established in "real space".

Just as Athena is the goddess of *creativity and divine intelligence*, and Hephaestus the god of *technology and making*, the contemporary practitioners needs to learn themselves to which one they should pray.

The arrival of Athena, the goddess, was feared by Zeus because of prediction that she would be more clever and more powerful than he. The relationships between Athena and Zeus presents an interesting symbolic parallel to architects and digital technology; just as Zeus was fearful of that which was not known, architects too are often wary of the effects of technology on their craft. However, as the mythology of Athena progresses, the goddess displays another unforeseen characteristic; and one that also should be of interest to the architect: Loyalty.

The loyalty of Athena for her father was not given, but rather is based on a developed relationship, born first of animosity, but one that progresses over time.

The current tradition of architecture is a field of adoption and repurposing; as technological innovations arise, architects are free to explore and interpret them for creative implementation; but only insomuch as their skills, experience, and knowledge allow. As with Zeus and Athena, the architect will profit if they engage in a relationship with technology, and over time, with persistence, understanding, and co-existence, the evolving relationship will bring more profit than cost.

The current popular understanding of the computer as simple tools is now out-dated. Digital and information technologies are in an almost persistent state of change, and because they are "intellectual technologies" their development actively invokes fundamental behavioural and intellectual change in users. Through a psychological acceptance of the "other" capabilities of computation, and an understanding of the *rhetorical* processes required for design, architects have the possibility to become party to the process of innovation, and invention.

Neither Athena nor Hephaestus alone is the embodiment of craft or technique, but rather each are both things simultaneously. The disfigured Hephaestus represents determination, technical mastery and the quest for beauty, while Athena is both beautiful is strong enough to stand alone, but she is also innovative and tactical. It is only through their strategic collaborations with others (Hephaestus with the Cyclopes, and Athena as counsellor to the hero's: Perseus, Odysseus, and Heracles), that these gods are able to overcome their own situations and become individuals within the larger context of Olympus.

They are both credited with bringing craftsmanship and inventiveness to mankind. Hephaestus is the bringer of technology, while Athena is the inventor of civilization; each in their own way representing a power over complexity. But it is their willingness to invest in methods, systems, strategy, …and collaboration, rather than relying on the fast but insincere godly magics, which brings them honour and recognition with men and the gods alike. Not only do they represent the patrons for architecture of the past, but also the virtues of technology and architecture for the future.

Athena represents the evolved traits of her Mother; Metis: the Titan goddess of "crafty thought and wise council". Those people who display creativity and cunning quickly win Athena's favour; and as such, it is clear that she should represent the architects. However the irony in comparing mythology and contemporary technology is that her embodied characteristics of creativity, divine intelligence, and wisdom, are precisely the subjective attributes that cannot be overtaken by rational digital technologies. In this respect, Athena represents the *balance* between technology and creativity, and it is within this balance that architects may find the inspiration for their future.

---

[i] Homer, "*The Odyssey - 13.6*", Samuel Butler, (ed.)

[ii] Hesiod, Theogony 886 ff (trans. Evelyn-White)

[iii] from: http://www.theoi.com/Olympios/Athena.html

[iv] http://en.wikipedia.org/wiki/Athena

Postamble

Glossary

Abstract or analytic system: is a pattern system whose elements consist of signs and/or concepts (language, mathematics, logic,…)

Alchemy: The medieval forerunner of chemistry, based on the supposed transformation of matter, esp. that of base metals into gold.

Algorithm: A process or set of rules to be followed in problem-solving, mathematics, or logical operations.

Array: An array is a systematic arrangement of objects. (data) A single entity, composed of highly structured and indexed sub-entities.

Astrology: Belief systems that holds that there is a relationship between astronomical phenomena and events in the human world

Attractors: are points, functions, or phenomena towards which a variable system evolves over time.

Autonomous agents: Programmed digital entities that carry out sets of operations with some degree of independence or autonomy, employing some codification of the overall goal. The programming is typically based on simple rule sets, but their ability to interact with other agents can create complex behaviours and *emergence* within systems.

Autonomous control-feedback loop: a positive feedback loop that affects and is affected by the system and its place within a greater environment. The stimuli are external to the system, but the effect of the system is also back onto that external environment.

Autopoiesis: The circularly organized processes of "self-creation" that characterize living systems, and, by extension, processes whose products include the processes that produce them.

Bifurcation: The splitting of a phenomenon or information into two distinct modes. Used here, bifurcation is the point at which a graph shows divergent activity, and where a graphed trend splits into two distinct paths.

Biomimetics: the study of the structure and function of biological systems as models for the design and engineering of materials and machines.

Black Box: A (fictional) construct applied by an observer at the location of some change in what is observed. The insertion of a Black Box allows a variable description to be developed for what might account for observed and yet-to-be observed changes, through the interaction of the observer and his Black Box.

Cellular automaton: is a discrete model studied in computation theory, which emulates a functioning cellular ecosystem. It produces *emergent* behaviour through a limited set of rules.

Circular causal relationship: see: autonomous control-feedback loop

Circularity: A looping process; where after a number of iterations the process ends up where it began. Recursive systems are circularities.

Chunk fabrication: A hybridisation of in-situ and prefabricated construction techniques, where large or complex components are preassembled off-site, but the primary assemblage of components occurs or is staged at a single site or factory.

Communication: (technology) The transference of data which may be interpreted as information.

Communication: (psychology); the act and means by which one system persuades another system to create an understanding (its own understanding).

Continuance: the ability of a system to maintain a steady state or steadily oscillating state.

Control: The act by which one (controller) system shapes the behavior of another (controlled) system, so that its behavior is more to the liking of the controller. However, investigation shows that control is circular and that controller and controlled are roles determined by an observer.

Conversation: A circular form of communication in which each participant constructs his own understanding. Checks on understandings between participants occur through re- presentation of individual understandings in a feedback loop. Conversation occurs between participants and is essentially interactive.

Cybernetics: "The study of circular causal, and feedback mechanisms in biological and social science" (Macy Conferences); later, "Communication and control in the animal and the machine" (Wieners eponymous book).

Degree: (geometry) – The degree of a spline is the highest power defining the polynomial equation (the algorithm) that defines the curve. A segmented polyline has a degree 2, higher degrees correspond to smoother polynomial definition: smoother curves.

Degree: (cybernetics) see: *Order.*

Delight: is the combination of understanding and surprise (rhetoric)

Digital Chain: The *digital chain* is the use of a contiguous set of data and different digital tools, combined to define, design, evaluate, produce, construct, complete, maintain and dispose of an architectural project.

Digital morphogenesis: computational techniques that are influenced by algorithms relevant to biological processes.

Disruptive technology: A disruptive technology is a technical innovation that changes an existing condition or instigates a new condition or value network. The disruptive technology eventually displaces the precedent technology.

Dominant design: established configuration that has achieved a dominant position of public or market acceptance. Typically entrenched such that it is not questioned or criticised; as such it is vulnerable to radical innovation.

Doxa: concerns matters of valuation, opinions and BELIEFS, such as if something is good or bad, beautiful or ugly, or conviction whether something is true or false even if it cannot be proven. *Doxa* can be interpreted as "doctrine" and that it "refers to general opinions within a group of people".

Early adopter: A practitioner or customer who adopts novel (or even unproved) phenomena: technology, systems, concepts, processes), despite the inherent business or technological risks. Risks are mitigated by potential early competitive gains and by developing early and more robust knowledge and experience with the innovation.

Elegance: (design) Elegance is process making high quality design that manages complexity, but is not complex itself.

Elegance: (programming) Elegant code is clean, spare, and easily understandable, while at the same time efficient, robust, and functionally effective. Elegance is derived from careful analysis of the problem, and the finding (or designing) of algorithms and structures which accomplishes the required management of complexity while still simplifying the code.

Emergence*:* The occurrence of complex systems and patterns that arise out of a multiplicity of simple interactions.

Energy: The ability to do work. The capacity of a physical system to imply force or momentum (either physical or conceptual) on other systems. Energy may be understood as either kinetic energy or potential energy; as seen in various *phases. Ex:* power, electricity, potential energy, embodied energy, and work.

Episteme: "The true knowledge" or "truth". Epistêmê concerns things that can be objectively and scientifically proved and that we therefore KNOW, such as 1+1 = 2.

Epistemology: What may be known, and how we can come to know this.

Exergy: The available energy in a system; the maximum useful work possible during a process that brings a system into equilibrium with its environment.

General Systems Theory: The interdisciplinary study of systems as a concept to explain interrelatedness and complexity in discreet phenomenon; as developed and published by vonBertalanffy.

Heuristics: Experience-based techniques of "trial and error" for problem solving, learning, and discovery. Also used colloquially to indicate "common rules" or rules of thumb, useful for making preliminary estimations.

High-level programming: Programming language using extensive semantic representation to abstract it from the computer. High-level languages typically use natural language elements to improve reading comprehension.

Holism: The concept (developed by Jan Smuts) that systems should be viewed as wholes, and that due to complex interrelatedness and emergent behaviour, systems have value that is greater than the sum of their parts.

Incremental innovation: innovation which is derived from an existing phenomenon; Incremental innovation modifies and extends an established design, but the underlying *architecture* (structure of components and their relationships) remains consistent.

Innovation: is the creation of novelty – something new. Innovation is a force (social, economic, technological,...) which invokes change in its context or situation.

Interaction: Mutual responsiveness that may lead to novelty, in which no participant has formal control over the proceedings. Interaction occurs between participants, not because of any one of them. Conversation epitomizes interaction in progress.

Invariance: is the property of perception whereby simple geometrical objects are recognized independent of rotation, translation, and scale

Iterative Innovation: (see: incremental innovation)

Knowledge Structures: (or knowledge networks) are conceptual structures that represent different aspects of knowledge related to single project or topic, and also depict the interrelatedness between the epistemological issues.

Maslows Hammer: "The law of the instrument"; The over-reliance on a familiar tool such that it is used and misused for every application.

Mass customization: The use of flexible methods; typically computer-aided design and manufacturing systems, to produce custom output from standardized or genotropic templates. Mass customization combines the low unit costs of mass production with the flexibility of individual customization.

Mass production: The production of large quantities of strictly standardized products using automated production methods. Mass production emphasises large numbers of product, produced quickly, at low-per-unit cost to offset the capitalization costs for the required machinery and infrastructure.

Methodology: An pre-defined guiding system for problem solving.

Multistability: is the tendency of ambiguous perceptual experiences to pop back and forth unstably between two or more alternative interpretations. (2D-axonometric cube)

Mutualism: The reciprocal arrangement by which what may be of one may be of the other.

Non-Euclidean Geometry: Geometry who's definition system does not adhere to Euclid's *parallel postulate*. Generically used to describe curvilinear non-uniform shapes commonly associated with NURBS; Spline, or free-form geometries.

NURBS: Non-Uniform Rational B-Splines; a mathematical system used to define curves and surfaces which is computationally efficient and has compact data structures. NURBS are commonly used for surface definition in CAD programs such as Rhino.

Observation: What the observer determines to be the results of a phenomenon or situation. Observation is not necessarily visual.

Order: The cybernetic *order* of a situation is the viewpoint taken in its scrutiny. Viewing a phenomenon itself is first order, investigating the viewing of a phenomenon is second order…

Paradigm: A set of assumptions, concepts, values, and practices that constitutes a fixed way of viewing reality for the community that shares them, especially in an intellectual discipline.

Paradigm paralysis: The inability to see beyond the current accepted paradigm or mode of thinking.

Paradigm-shift: A conceptually revolutionary change from one established way of thinking and paradigm to replace it with another; Paradigm-shift is is driven by innovation or other agents of change.

Polysemic paradigms: A special condition of paradigm where the context is objectively unquantifiable or speculative. In such conditions multi-paradigmatic conditions are considered polysemic: Used in subjective and speculative fields such as the humanities, and including design.

Positivism: Theory positive knowledge is based on natural and observable phenomena, and their properties and relations as verified by the empirical sciences

Prefabrication: the stages manufacture of sections of a project, typically at a factory so they can be easily and rapidly assembled.

Radical Innovation: Innovation that changes both the components and the architecture of an existing product, phenomenon, or situation.

Rationalism: A belief that logic and observable facts are the foundation of certainty in knowledge. Rational actions should be based on reason and knowledge, rather than on opinion, or emotional response.

Real system*:* Any system of matter and/or energy (biological, mechanical, physical…)

Recursion: Literally "backward movement"; A process by which the response to a statement raises that statement again, as found in self-referential systems.

Reflection-in-action:"Thinking on your feet" This is intellectual reflection that occurs whilst a problem is being worked; it is typically stimulated by curiosity or surprise, by something puzzling to the practitioner.

Reflection-on-action: The retrospective contemplation of practice undertaken in order to uncover the knowledge used in practical situations, by analysing and interpreting the information recalled.

Reflective Practice: An iterative theory of practice-based "learning from doing" where individuals learn from their own experience, and then consciously apply the learned experience to foster intuition, and skills. When applied to design it creates a cyclical process of analysis, testing, evaluation, and synthesis.

Reification: Reification is the constructive or generative aspect of perception, by which the experienced percept contains more explicit spatial information than the sensory stimulus on which it is based.

Resolution: (visual, data, processing,…) The amount of detailed information in a unit measure of phenomenon. A comparative measure of information density.

Second Order Cybernetics : The study of cybernetics from a point of view informed by the understandings developed in cybernetics: "The cybernetics of cybernetics", investigates the construction of models of cybernetic systems.

Stimuli: A thing or event that evokes a specific functional reaction in responsive system.

Systems Architecture**:** the structural, organizational, logistical, and operational composition of a design, product or process, differentiated from Architecture – the design and production of buildings - in this text by always italicizing the word.

Theurgy*:* The operation or effect of a supernatural or divine agency in human affairs.

Transmutations: conversion from one thing into a separate second thing, associated with alchemy. *Ex: Water into wine, brass into gold.*

Trickle-down effect: (technology) The propensity for technologies or services to become common over time, and become increasingly available to the lessor trades or professions. The name is derived from "trickle down economics".

Versioning: The use of the concept genotype definitions to create variability (versions) of design. This concept has emerged into the parametric and generative design.

Vitruvian virtues: "A structure must exhibit the three qualities of *firmitas, utilitas, venustas*: it must be solid, useful, and beautiful.

Bibliography

"For I cannot invent new kinds myself at this late day, nor do I think that I ought to display the inventions of others as my own. Hence, I will mention those that have come down to us, and by whom they were invented." – Vitruvius (30.BC) "*The Ten Books of Architecture*": p.272.

Books:

Addington, M., Schodek, D. (2005). "Smart Materials and New Technologies for the Architecture and Design Professions". Oxford: Architectural Press, Boston, MA. ISBN: 978-0750662253

Alexander, C. et al. (1977) *"A Pattern Language"*. Oxford University Press: New York, NY. ISBN: 978-0195019193

Argyris, C., Schön, D. (1974) *Theory in practice: Increasing professional effectiveness*, San Francisco: Jossey-Bass. ISBN: 978-1555424466

Berlinski, D. (1999). *The Advent of the Algorithm: The Idea that Rules the World*. Houghton Mifflin Harcourt. Boston, MA. ISBN: 978-0151003389

Braham, W. and Hale, J. (eds.) (2007) "*Rethinking technology*" Routledge, Taylor and Francis Group, London. ISBN: 978-0415346535

Brown, T. Katz, B., (2009). "*Change by Design*". Harper Collins Publishing, New York. NY. ISBN: 978-0-06-176608-4

Cache, B., (1995) "*Earth Moves:The furnishing of Territories*", MIT Press, Cambridge. ISBN: 978-0262531306

Cahola Schmal, P. (ed) (1998)"*Digital Real: Blobmeisters, first built projects*", Birkhäuser, Berlin. ISBN: 978-3764365721

Carr, N. (2010) "T*he Shallows: How the internet is changing the way we think, read and remember*", Atlantic Books, London. ISBN: 978-1-84887-226-4

Chomsky, N. (2002). *"Syntactic Structures"*. Walter de Gruyter (reprint from 1957): Boston, MA. ISBN: 978-3110172799

Christensen, C.M. (1997) *The Innovator's Dilemma*, Harper Paperbacks, New York. ISBN: 978-0060521998

Christensen, C.M. (2003) *The Innovator's Solution*, Harvard Business School Press, Cambridge. ISBN: 978-1578518524

Clark, G. (2007) "*A Farewell to Alms: A Brief Economic History of the World*" Princeton University Press. ISBN: 978-0-691-12135-2.

Clarke, D.M. (ed.) (2012) *"Meditations and Other Metaphysical Writings"* Penguin Classics: London. ISBN: 978-0140447019

Coates, P. (2010) "*Programming Architecture".* Routledge, New York. 2010. ISBN: 978-0-4518888

Cobbers, A., Gössel, P., Jahn, O. (2010) "*PreFab"*, Taschen Books. Köln, DE ISBN: 9783836507530

Cross, N., (ed.) (1984) "*Developments in Design Methodology"*, Chichester, UK: John Wiley & Sons Ltd. ISBN: 978-0835727990

Cross, N., (2011) "*Design Thinking"*, Berg, Bloomsbury Publishing, NY, NY. ISDN:978184788636-1

Cross, N (2007) "*Designerly ways of knowing*". Springer, New York. ISBN: 978-184 9965736

Cross, N., et al. (eds.) (1996) "*Analysing Design Activity*", Chichester and New York, John Willey and Sons. ISBN: 978-0471960607

Cuff, D. (1991). "*Architecture: The Story of Practice"* (Cambridge, MA: MIT Press, 1991). ISBN: 978-0262031752

DeLanda M. (1997) "*A Thousand Years of Nonlinear History*", Zone Books-Swerve Editions, New York. NY. ISBN: 978-0942299328

Deleuze, G. (1988) "*Le Pli*" Les éditions de Minuit, Paris. ISBN: 978-2707311825

Deleuze, G. (1995), *"Negotiations. 1972-1990"*, Columbia University Press: NY. ISBN: 978-0231075817

Deleuze, G & Guattari, P. (1987) *"A Thousand Plateaus".* University of Minnesota Press. ISBN: 978-0816614028

Deleuze, G. & Guattari, F. (1996), *"What is Philosophy?",* Columbia University Press: New York. ISBN: 978-0231079891

Dewey, J. (1933) "*How We Think*". Dover Publications, New York. (reprint 1997); ISBN 978-0486298955

Dewy, J. (1938) "*Logic : The theory of Inquiry.*" New York: Irvington Publishing (reissue: 1980). ISBN: 978-0891978312

Dienel, Hans-Liudger, (1995). *"Ingenieure zwischen Hochschule und Industrie. Kältetechnik in Deutschland und Amerika, 1870-1930".* Göttingen: Vandenhoeck & Ruprecht.

Derrida, J. (1976) "*Of Grammatology",* (trans. Gayatri Chakravorty Spivak) Johns Hopkins University Press, Baltimore & London. ISBN: 978-0801858307

deSola-Morales, I. (1996), *"Differences: Topographies of Contemporary Architecture"*, MIT Press, Cambridge. ISBN: 978-0262540858

Engle, H. (1967). "*Structure Systems*". DVA Verlag; Stuttgart. ISBN: 9783775718769

Hesiod (B.C) "*the Homeric Hymns, and Homerica*". H.G. Evelyn-Whyte, (trans.), Cambridge, Mass.: Harvard Leob Classical Library, 1914.

Fludd, R. (1659):"Mosaical Philosophy". London, Humphrey Moseley.

Flusser, V. (1999). *"The Shape of Things".* Reaktion Books, London, UK. ISBN: 978-1861890559

Frazer, J. (2003) *"An Evolutionary Architecture"*, Architectural Association Publications, London. ISBN: 978-1870890472

Galofaro, L. (1999) "*Digital Eisenman: An Office of the Electronic era"* Birkhauser, Basel. ISBN: 978-3764360948

Ghirardo, D. (1990) *"Architecture After Modernism."* Thames & Hudson: London, UK. ISBN: 978-0500202944

Grabow, S. (1983) "*Christopher Alexander: The Evolution Of A New Paradigm In Architecture*", Routledge Kegan Paul, London. ISBN: 978-0853621997

Hazzan, O., Tomayko, J., (2005) "*Human Aspects of Software Engineering"*, Laxmi Publications, New Delhi, India. ISBN: 978-8170087182

Hebeisen, W. (1999) "*F.W. Taylor und der Taylorismus. Über das Wirken und die Lehre Taylors und die Kritik am Taylorismus.*" VDF Hochschulverlag AG, Zürich, CH. ISBN: 978-3728125217

Hensel, M. et al. (2010) "*Emergent Technologies and Design*," Routledge Press, New York. ISBN: 978-0415493444

Hensel M. et al. (eds): 2006, *Techniques and Technologies in Morphogenetic Design*, Wiley-Academy, Great Britain.

Hilbert, D., et al. (2002)., *"Grundlagen der Geometrie"*, Teubner, Germany.

Holm, Ivar (2006). *"Ideas and Beliefs in Architecture".* Oslo School of Architecture and Design. Oslo, NO. ISBN: 8254701741

Imperiale, A. (2000) "*New Flatness: Surface Tension in Digital Architecture*", Birkhäuser, Basel. ISBN: 978-3764362959

Iwamoto, L. (2009). "*Digital Fabrications: Architectural and Material Techniques",* Princeton Architectural Press; New York. ISBN: 978-1568987903

Jacobs, J. (1961). *"The Death and Life of Great American Cities",* Modern Library; First Edition (1993), New York. ISBN: 978-0679600473

Jackson, F. (1998), "*From Metaphysics to Ethics: A Defence of Conceptual Analysis"*. Oxford: Clarendon Press. ISBN: 978-0198250616

Jencks, C. (1971). *"Architecture 2000: Predictions and Methods"*. International Thomson Publishing: London, UK. ISBN: 978-0275492809

Jenks, C. (2002) *The New Paradigm in Architecture, The Language of Post-Modern Architecture (7th ed.)*, Yale University Press, London, New Haven. ISBN: 978-0300095135

Johnson, P.A. (1994) *"The theory of architecture: concepts, themes, and practices"* London: Wiley Academy. ISBN: 978-0471285335

Jones, John Christopher, (1970) "*Design Methods: seeds of human futures*", John Wiley & Sons Ltd., London

Kelly, K. (1994) *Out of control: the new biology of machines, social systems and the economic world*. Addison- Wesley, Boston. ISBN: 978-0201483406

Kieran, S. + Timberlake, J. (2003) *"Refabricating Architecture: How Manufacturing Methodologies are Poised to Transform Building Construction"* McGraw-Hill Publishing, New York. ISB: 978-0071433211

Kolarevic, B. (2003) "*Architecture in the Digital Age: Design and Manufacturing*" Taylor & Francis Group. New York. ISBN: 978-0415381413

Kolarevic, B., Malkawi, A. (2005) "*Performative Architecture: Beyond Instrumentality*", Taylor & Francis Group. New York. ISBN: 978-0415700832

Kolarevic, B., Klinger, K. (2010) *"Manufacturing Material Effects: Rethinking Design and Making in Architecture"*. Routledge Press, New York. ISBN: 978-0415775755

Kuhn, T.S. (1977) "The Essential Tension: Selected Studies in Scientific Tradition and Change". University Of Chicago Press, Chicago, Il. ISBN: 978-0226458069

Kuhn, T.S. (1996) "The Structure of Scientific Revolutions", 3rd Edition, University Of Chicago Press, Chicago, Il. ISBN: 978-0226458083

Kurzweil, R. (1992) "*The Age of Intelligent Machines*". MIT Press, Cambridge, MA. ISBN: 978-0262610797

Kurzweil, R. (2006) "*The Singularity Is Near: When Humans Transcend Biology*". Penguin, London, UK. ISBN: 978-0143037880

Laurel, B. (2003) *Design Research: Methods and Perspectives,* Cambridge: M.I.T. Press. ISBN-13: 978-0262122634

Lawson, B (1980) "*How designers think*". Architectural Press, Eastview Editions, NJ. ISBN: 978-0750660778

Lindsey, B. and Gehry, F. (2001) *Digital Gehry: Material Resistance, Digital Construction.* Berlin: Birkhäuser. ISBN-13: 978-3764365622

Livesay, Harold C. (2006). *"Andrew Carnegie and the Rise of Big Business",* 3rd Edition. Boston: Longman Publishing. ISBN-13: 978-0321432872

Lynn, G. (1999) "*Animate form*". Princeton Architectural Press, New York ISBN: 978-1568980836

Lyons, William (1986), *The Disappearance of Introspection*. Cambridge, MA: MIT Press.

Maslow,A., (1966) *"The Psychology of Science",* Maurice Basset Publishing, New York, ISBN: 978-0895269720

McLuhan, M.(1994). *Understanding Media: The Extension of Man*, (reissued from 1964).The MIT Press, Cambridge, MA. ISBN: 978-0262631594

McLuhan, M.(2005). *The Medium is the Message,* (reissued from 1967). Gingko Press; Berkley, CA. ISBN: 978-1584230700

Meikle, J.L. (1997). *"American Plastic: A Cultural History"* Rutgers University Press, London, UK. ISBN: 978-0813522357

Moggridge, W. (2007), *Designing Interactions,* MIT Press, Cambridge, MA. ISBN:978-0262134743

Morgan, M.H (trans) (1960) *"The Ten Books of Architecture".* (trans from Vitruvius – 30 BC): Dover Publications, New York. 1960. ISBN: 486-20645-9

Mori, T. (2002) *Immaterial / Ultramaterial: Architecture, Design, and Materials.* Harvard Design School press/ George Braziller, Cambridge, MA. ISBN: 978-0807615089

Munari, B. (2008) *"Design as Art". (*Republished: 1966, Editori Laterza: Creagh, P. (Trans) (1971)). Penguin Books. London, UK. ISBN:978-0141035819

Negroponte, N. (1970). "*Architecture Machine*", M.I.T. Press, Cambridge, MA. ISBN: 9780262640107

Nesbitt, K. (ed.) (1996) *"Theorizing a new agenda for architecture: an anthology of architectural theory 1965-1995."* Princeton Architectural Press; 2nd edition (1996). ISBN: 978-1568980546

Newell, A., Simon, H.A. (1972). "*Human Problem Solving*". Englewood Cliffs, N.J.: Prentice-Hall. ISBN: 978-0134454030

Nisbett, R. (2003). *The Geography of Thought: How Asians and Westerners Think Differently...and Why*. Free Press. ISBN: 978-0743216463

Ong, W.J. (1982) "*Orality and Literacy: The Technologizing of the Word*." Routledge Press, New York. ISBN: 978-0415281287

Oxman, R. and Oxman, R. (eds) (2010). "T*he New Structuralism: Design, Engineering And Architectural Technologies"* Architectural Design, Vol 80, No 4. July/August 2010. Wiley Printing, London, UK. ISBN: 978-0470-742273

Pearce, P. (1990) "*Structure In Nature As a Strategy For Design."* MIT Press, Cambridge, MA. ISBN: 0262-16064-1

Peters, T.F. (1996) *"Building the Nineteenth Century."* The MIT Press, Cambridge, MA. ISBN: 978-0262161602

Pietikäinen, P. (2001) *"C.G. Jung and the psychology of symbolic forms".* Finnish Academy of Science and Letters, Helsinki, FN. ISBN: 978-9514108570

Pine, J. (1992) *"Mass Customization: The New Frontier in Business Competition"* Harvard Business School Press, Cambridge, MA. ISBN: 978-0875843728

Porter, R. and Teich,M. (1986) *Revolutions in History*. Cambridge University Press, Cmbridge, UK. ISBN-13: 978-0521277846

Postman, N. (1993) "*Technopoly: The surrender of Culture to Technology*", New York: Vintage Publishing. ISBN: 978-0679745402

Rahim, A.(2006) *Catalytic Formations: Architecture and Digital Design*. New York: Taylor & Francis. ISBN: 978-0415390897

B. Raphael, I.F.C. Smith. (2003). "*Fundamentals of Computer Aided Engineering*". John Wiley, UK. ISBN: 978-0471487159

Reiser. J. "*Atlas of novel tectonics, Reiser + Umemoto*". Princeton Architectural Press: New York. ISBN: 978-1568985541

Roth, L.M. (1993) "*Understanding Architecture: Its Elements, History, And Meaning*". Westview Press, Oxford, UK. ISBN: 978-0064301589

Ruby, I., and Ruby, A. (eds). (2010) "*Re-inventing Construction*". Ruby Press: Berlin, DE. ISBN 978-3-9813436-2-5

Sauer, C. (2010) "*Made Of... New Materials Sourcebook for Architecture and Design*". Die Gestalten Verlag. Berlin, DE. ISBN: 978-3899552898

Schodek, D.L., et al. (2004) "*Digital Design and Manufacturing: CAD / CAM Technologies in Architecture"* John Wiley & Sons, New York, NY.

Schön, D A., (1963), *Displacement of Concepts*, Tavistock Publications, London. ISBN: 9780422710909

Schön, D A., (1967), *Technology and Change: The New Heraclitus*, Delacorte Press: New York.

Schön, D. A., (1991), *The Reflective Practitioner: How Professionals Think in Action.* Arena Ashgate Publishing Limited, 1991, London, UK. (re-issued: 1983) ISBN: 978-1857423198

Schön, D. A., (1990), *Educating the Reflective Practitioner.* Jossey-Bass Publishing Limited, London, UK. ISBN: 978-1555422202

Schröpfer, T. (2010) *"Material Design"* Birkhäuser Architecture, Basel. ISBN: 978-3034600354

Schulze, F. (1995) "*Mies Van Der Rohe: A Critical Biography*". University of Chicago Press, Chicago, IL. ISBN: 978-0226740607

Schmall, P.C. (2004) *Workflow: architecture e engineering*. Birkhäuser, Basel. ISBN: 978-3764370954

Sennet, R. (2010) "*The Crafstman".* Penguin Publishing, London, UK. ISBN: 978-0141022093

Simon, H A (1969) *The Sciences of the Artificial*, Cambridge, MA: MIT Press. ISBN: 978-0262691918

Steel, J., (2002) "Architecture and Computers: Action and reaction in the digital design revolution". Watson Guptill Publications, New York. ISBN: 0823003248

Stiny, G (2006) "*Shape: talking about seeing and doing*" MIT Press, Cambridge, MA ISBN: 978-0262693677

Stolterman, E. et al. (2007) "*Thoughtful Interaction Design: A Design Perspective on Information Technology"* (2nd edition) MIT Press. Cambridge, MA. ISBN: 978-0262622097

Tayor, F.W. (1911) "*The Principles of Scientific Management",* (reprint 1967). Harper & Row, Publishers, New York. ISBN 0-393-003981

Terzidis, K. (2006) *Algorithmic Architecture,* Boston: Architectural Press, ISBN: 978-0750667258

Thorn, R. (1994) *Structural Stability and Morphogenesis,* Westview Press: London, UK. ISBN: 978-0201406856

Tostrup, E. (1999), *"Architecture and Rhetoric: Text and Design in Architectural Competitions",* Andreas Papadakis Publishers: London, UK. ISBN: 978-1901092059

Toulmin, S., (1990) *Cosmopolis. The Hidden Agenda of Modernity*. Chicago: University of Chicago Press. ISBN: 978-0226808383

Tournikiotis, P. (2002) *"Adolf Loos"* (4th edition), Princeton Architectural Press; New York. ISBN: 1568983425

Trilling, J., (2001) *"The Language of Ornament"*, Thames and Hudson, London. ISBN: 9780500203439

Turnbull, R., (1998) *"The Parmenides and Plato's Late Philosophy".* University of Toronto Press, Toronto, CA. ISBN: ISBN 9780802042361

Van Berkel, B., Bos, C. (1999) "*Move".* Architectura and Natura, Amsterdam. ISBN: 978-9076863719

Van Berkel, B., Bos, C.(2006). "*UN Studio: Design Models - Architecture, Urbanism, Infrastructure*", Rizzoli Publishing, New York. ISBN: 978-0847828784

von Bertalanffy, L. (1969). *"General System Theory: Foundations, Developments, Applications"* (revised edition 1969). NewYork: George Braziller Inc. :978-0807604533

Weston, R. (2003) "*Materials, Form and Architecture"*, Laurence King Publishing Ltd, London, 2003, 79 ISBN: 978-0300095791

Wiener, N. (1964) *"I Am a Mathematician.*" Cambridge, MA : MIT Press. ISBN: 978-0262730075

Wiener, N. (1948), *"Cybernetics: Or Control and Communication in the Animal and the Machine*". Cambridge, MA : MIT Press ISBN 9780262730099; (2nd ed. 1961)

Wingler, H.M. (1978). "*Bauhaus: Weimar, Dessau, Berlin, Chicago*" MIT Press, Cambridge, MA. ISBN: 978-0262730471

Woodbury, R. (2010) "Elements of Parametric Design", Routledge Press, New York. ISBN: 978-0-415-77986-9

Yates, Frances A. (1966). *The Art of Memory.* Chicago: University of Chicago Press. ISBN 10226950018

Yeomans, D. (1997). *"Construction Since 1900: Materials"* Batsford Ltd: London, UK. ISBN: 978-0713466843

Zaero-Polo, A., Moussavi, F. (2003) "*Phylogenesis: FOA's ark*". Actar, Barcelona, ES. ISBN: 978-8495951472

Zellner, P. (ed) (1999) "*Hybrid space: new forms in digital architecture*". Thames and Hudson, London, UK. ISBN: 978-0847822034

Articles, essays & papers:

Alexander, C. (1967) *"The Question of Computers in Design"* in: *Landscape.* No.14, vol.3. Autumn 1965. Pp 8-12.

Archer, L B (1979) "Whatever Became of Design Methodology?", in: *Design Studies*, Vol 1(1): pgs. 17-20

Aish, R. (2006) "*Instrumental Geometry*", In: *Architectural Design*, Vol 76, Issue 2. London: Wiley Academy Editions: p.42-53

Bahloul, R., et al. (2006), "*Optimisation of springback predicted by experimental and numerical approach by using response surface methodology*". In: Journal of Materials Processing Technology. 173(1): p. 101.

Bertalanffy, L.v. Zu Einer Allgemeinen Systemlehre. in: Biologia Generalis no.195, MIT Press (1948) Cambridge MA. pp.114-129

Bazjanac, V. (2004), "Virtual Building Environments (VBE), Applying Information Modeling to Buildings," in: *Conference on Product and Process Modeling in the Building*, 2004, 1.

Benedikt, M. (1999), *"Less for Less Yet".* In: Harvard Design Magazine, Winter / Spring 1999.

Bezier,P. (1974), *"Mathematical and Practical Possibilities of UNISURF"*, In: R.E. Barnhill and R.F. Riesenfeld (eds.) *Computer Aided Geometric Design*. p.127 – 152.

Brooks, H. (1967) "*Dilemmas of Engineering Education.*" In: *IEEE Spectrum*, Feb 1967: 89-91

Buchanan, R. (1995), *"Rhetoric, Humanism, and Design"*, in: R. Buchanan & V. Margolin (eds.) *Discovering Design. Explorations in Design Studies*, Chicago: The University of Chicago Press.

Burry, M. (1998) *"Paramorph"* in. Stephen Perrella (ed.), *Hypersurface Architecture:* AD Profile 141. London: Wiley Academy Editions.

Burry, M and Murray, Z (1997) *Computer aided architectural design using parametric variation and associative geometry*, in: Challenges of the Future, ECAADE Conference Proceedings, Vienna.

Carpo, M. (2008) *"Non Standard Morality: Digital technology and its discontents."* In: Vidler, A. (ed.) *Architecture Between Spectacle and Use*, Yale University Press. New Haven, CT: pgs. 127-142.

Celento, D. (2007). "Innovate or Perish: New Technologies and Architecture's Future" in: Harvard Design Magazine, Spring/Summer 2007, Number 27. Cambridge, MA.

Chaszar, A, Kienzl, N and Stoller, P (2006) "*Environmental engineering: integrating computer simulation into the design process*" in: A Chaszar (ed) *Blurring the lines.* John Wiley & Sons Ltd. London, UK.

Christiaans, H., and Restrepo, J. (2004) "*Problem Structuring and Information Access in Design*" In: *Journal of Design Research*; Volume 4, Issue 2; 2004.

Clark, K. (1987) "*Managing technology in international competition*" In: Spence, M. and Heather Hazard (eds.), *International Competitiveness*. Cambridge. MA: Ballinger: p:27-74

Coorey, B., Jupp, J. (2010) "*Parametric Modelling And Design Processes*". In: Gu, N. (ed.) *CAADRIA 2011, Circuit Bending Breaking and Mending,* University of Newcastle.

Cross, N (1982) "*Designerly ways of knowing"* in: *Design Studies* Vol 3,no 4.:221-227

Cross, N (2001) "*Designerly ways of knowing; design discipline vs. design science*" in: *Design Issues* Vol 17 No 3. p:49-55

Cuff, D. (2001), *"Digital pedagogy: an essay: one educator's thoughts on design software's profound effects on design thinking and teaching"* In: *Architectural Record*, September 2001.

Deamer, P. (2006) *"Branding the Architectural Author."* In: *Perspecta: Famous,* Vol. 37: 44-66.

DeLanda, M. (2001), *"Philosophies of Design. The Case of Modeling Software"*, In: A. Ferré, et al. (eds.) *Verb Processing*, Actar Press: Barcelona ISBN: 978-8489698888

Derix, C. *In-Between Architecture Computation*, in *IJAC*: issue 04, vol. 07 pg.565-585

Dorst, K., and Dijkhuis, J. (1995) Comparing paradigms for describing design activity, in *Design Studies*, 16(2), pp 261-274.

Dritsas, S. et al. (2006), Computational Methods on Tall Buildings. in eCAADe 2006.

Dritsas,S. Kashyap, S. (2004), "Scripted Mockups" In: *CAADRIA 2005 Conference Proceedings*, Delhi, India. ISBN: 81-902816-0-7

Fricker, P. et al. (2004) 'Microarchitecture" in: *Detail Magazine* -12/04: p.1484-1487

Gage, S.A. (2006) *The wonder of trivial machines*. In: *Systems Research and Behavioral Science* , issue 23, vol.6. pp. 771-778

Garber and Jabi (2004). "*Control and Collaboration: digital fabrication strategies in academia and practice*." in: *IJAC*. issue 02, vol 04:p.121

Gero, J.S. (1990) "*Design Prototypes: A Knowledge Representation Schema for Design*", in *AI Magazine.* vol11. Issue 4, pp 26-36.

Gero, J. S. (1994), "*Towards a model of exploration in computer-aided design*". In: J. S. Gero and E. Tyugu (eds), *Formal Design Methods for CAD*, North-Holland publishing, Amsterdam, pp. 315–336

Gero, J. S. (1996) "*Creativity, emergence and evolution in design*", in *Knowledge-Based Systems*, 9, pp 435-448.

Goldman, Alvin I. (1997), *"Science, Publicity, and Consciousness",* in *Philosophy of Science* issue 64: 525-545.

Gonchar, J. (2006) *"Tech Briefs: To Architects, Building Information Modeling Is Still Primarily a Visualization Tool,"* in: *Architectural Record,* July, 2006. Vol.30 no.6.

Hall, A. Rupert, (1974) "*What did the Industrial Revolution in Britain owe to Science?*', in: Neil McKendrick (ed.). *Historical Perspectives: Studies in English Thought and Society*, London: Europa Publications: 129-151.

Hazzan, O. and Tomayko, J., (2005) Reflection and abstraction processes in the learning of the human aspects of Software Engineering, in: IEEE Computer, pp. 39-45, June 2005.

Henderson, R.M., Clark, K. (1990) "*Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms*". In: *Administrative Science Quarterly*, Vol. 35, No. 1, Special Issue: *Technology, Organizations, and Innovation*. (Mar., 1990), Johnson Graduate School of Management, Cornell University: pp. 9-30.

Hensel, M. et al. (2004) "*Emergence: Morphogenetic Design Strategies*", In *Architectural Design* vol 73 no.7, London: Wiley Academy.

Hensel, M. and Menges, A. (2009), *Patterns in Performance-Orientated Design*, in *Architectural Design*, Vol 79, No 6 (November/December 2009), pp. 88 to 93.

Heylighen F., Joslyn C. (2001): "*Cybernetics and Second Order Cybernetics*", in: R.A. Meyers (ed.), *Encyclopaedia of Physical Science & Technology,* Vol. 4 (3rd ed.), Academic Press, New York, p. 155-170

Jenks, C. (1997) *"New Science - New Architecture?"* in: *Architectural Design - AD*, special issue # 129, December 1997.

Khoshnevis, B. (1998) *"Innovative Rapid Prototyping"* in: *Material Technology*, vol 13(2): p53-56

Killian, A. (2003) *"Fabrication of partially double-curved surfaces out of flat sheet materials through a 3d puzzle approach"'* in: *ACADIA 2003: Connecting Crossroads of Digital Discourse*, 74-81. Association for Computer Aided Design In Architecture, Indianapolis.

Kipnis, J. (1993) *"Toward a New Architecture."* In: Lynn, G. (ed.) *AD: Folding and Pliancy,* AD Profile No 172. p:40-49 Academy Editions, London.

Knight, T (1999) "*Shape grammars in education and practices: history and prospects"*. In: *International Journal of Design Computing* (IJDC) Vol 2. MIT Press. Cambridge, MA.

Knight, T and Stiny, G (2001) "*Classical and non-classical computation"* in: *Architectural Research Quarterly*, Cambridge Journals Vol 5.p:355-372

Kvan, T, Mark, E, Oxman, R and Martens, B (2004) "*Ditching the dinosaur: redefining the role of digital media in education"* in: IJDC: No 5. MIT Press, Cambridge.

Kwinter, S. (1998), *"Leap in the Void: A New Organon?",* In: C. C. Davidson (ed.) *Anyhow.* The MIT Press: Cambridge, MA. ISBN: 978-0262540957

Kwinter, S. (2006) *"The Judo of Cold Combustion"* in: Reiser. J. *Atlas of novel tectonics*, Reiser + Umemoto. Princeton Architectural Press: New York.

Lam, K. P., Yeang, K. (2009). *"Computational Building Performance Modelling and Ecodesign."* In: *Architectural Design*, 79(5), pgs.126-129.

Leach, N. (2010) *"Parametrics Explained".* in Neil Leach, Xu Wei-Guo (eds.), *Maschinic Processes, Architecture Biennale Beijing – Volume 1: Architects.* Beijing: China Architecture and Building Press.

Leach, N. (2008) '*New Materialism*' in Neil Leach, Xu Wei-Guo (eds.), *(Im)material Processes: New Digital Techniques for Architecture, Volume 2: Students*, Beijing: China Architecture and Building Press, 2008.

Legendre, G.L. (2011) *"The Mathematics of Sensible Things.*" In: *Architectural Design*: Volume 81, Issue 4. London: Wiley Academy.

Levit, R. (2008) *"Contemporary Ornament; The Return of the Symbolic Repressed"* in *Harvard Design Magazine*, Spring/Summer 2008, Number 28.

Liu Y T (2006) *New tectonics: a preliminary framework involving classis and digital thinking* in: Oxman, R. (ed.) A Special Issue on Digital Design, Design Studies Vol 27 No 3 p.267-307

Logan B., Smithers, T (1993) "*Creativity and design as exploration*" In: Gero, J.S. and Maher, M. (eds.) *Modeling Creativity and Knowledge-Based Creative Design: pgs.*139-175.

Loukissas, Y. (2003), *"Rulebuilding, Exploring Design Worlds through End-User Programming"* MArch thesis, Department of Architecture, MIT, Cambridge, MA.

Loveridge, R. (2004), *"The Machinic Process"* in: *ACADIA 2004: Examining the Digital Practice of Architecture*, 316-318. Toronto: Association for Computer Aided Design In Architecture

Loveridge, R. (2010). "*Fantastic Form: Digital Design as Fiction and Fact*" In: "Swiss Design Network conference 2010: Design Fictions" Institut Design und Kunstforschung: IDK, Fachhochschule Nordwestschweiz. Basel, CH. ISBN: 978-3-9523662-19

Loveridge, R. (2011) *"The Digital Design Paradox".* In: D. Kuhlmann, S. Brell-Cokcan, K. Schinegger (eds.) *"e-Motion".* Luftschacht Verlag: Wien, ISBN: 978-3-902373-86-1

Loveridge, R. and Strehlke, K. (2004). *"The Rustizierer: A dimensional translation of antiquity into technology".* In: *TransLate:* Trans vol 12. ed. H. Bindl, 52-59. Zurich: GTA Verlag - ETH Press.

Loveridge, R. and Strehlke, K. (2005), *"The Redefinition of Ornament: Using Programming & CNC Manufacturing"*, In: *CAADfutures 2005 Proceedings* - Vienna University of Technology, Vienna, Austria

Loveridge, R. and Strehlke, K. (2006*),"The Digital Ornament using CAAD/CAAM Technologies ",* IJAC - International Journal of Architectural Computing, Volume 4, Number 1, January 2006

Lynn, G. (1993), *"Arch. & Curvilinearity"* in: *Folds, Bodies and Blobs: Collective Essays* (1998)

Lynn, Greg. (1992) "*Multiplicitous and Inorganic Bodies*; in *Architectural Design* 63:3/4 (1992) pp. 125-7

Mark, E., Martens, B. and Oxman, R. (2003) "*Preliminary stages of CAAD education*" in: *Automation and Construction* Vol 12, no 6. p 661-670

McCormack, J., et al. (2004) "*Generative Design: a paradigm for design research*" in: Redmond, J. et. al. (eds.) *Futureground, Design Research S*ociety: Melbourne, AUS.

Mitchell,W.J. (1999), *"A Tale of Two Cities: Architecture and the Digital Revolution"* in: *Science,* August 1999: Vol. 285 no. 5429 pp. 839-841.

Mitchell,W.J. (2005), *"Constructing Complexity"*, in: Martens, B., Brown,A., eds., *Computer Aided Architectural Design Futures 2005*, Springer, Vienna.

Oosterhuis, K. et al. (2004), *"File to Factory and Real-Time Behaviour in ONL-Architecture"* In: *ACADIA 2004: Examining the Digital Practice of Architecture*, 294-303. Toronto: Association for Computer Aided Design In Architecture

Oxman, R (2004) "*Think-maps: teaching design thinking in design education*". in: *Design Studies.* Vol 25, No 1:pp 63-91

Oxman, R. (2005) "*Theory and design in the first digital age*" in: *Design Studies* Vol 27 No 3 p.229-265

Oxman, R. (2008) "*Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium*" In: Candy, L. and Costello, B. (eds) *Design Studies,* Vol 29 No. 2. March 2008, pp99-120

Oxman, R, Hammer, R and Ben Ari, S (2007) "*Performative design in architecture"*, in: ECAADE 2007, Wiesbaden and Frankfurt, DE.

Ozkar, M (2007) *Learning by doing in the age of design computing*, in: *CAAD Futures, Proceedings of the 12th International Conference on Computer Aided Architectural Design Futures*, Sydney, Australia,: pgs.99-112

Pask, G. (1971) '*A comment, a case history and a plan'*, in: J Reichardt (ed), Cybernetics, Art and Ideas, Graphic Society Ltd and Studio Vista. London, UK.

Paulinyi, A. (1982) *"Der Technologietransfer für die Metallbearbeitung und die preußische Gewerbeförderung (1820-1850)"*, In: *Schriften des Vereins für Socialpolitik, Gesellschaft für Wirtschafts- und Sozialwissenschaften*, Neue Folge. Issue:125, pgs.99-141.

Paulinyi, A. (1986) *"Revolution and Technology"*, in: Roy Porter and Mikulas Teich (eds.). *Revolution in History,* Cambridge: Cambridge University Press: pgs.261-289.

Paulinyi, A. (1991). *"Die Umwälzung der Technik in der Industriellen Revolution zwischen 1750 und 1840"*, in: Akos Paulinyi and Ulrich Troitzsch. *Mechanisierung und Maschinisierung 1600 bis 1840. Propyläen Technikgeschichte* volume 3. Berlin: Propyläen, 269-495-73.

Rahim, A. (2002) "Introduction" In: Rahim, A. (ed.) *Contemporary Techniques in Architecture*: AD Vol 72, No 1 Jan 2002.

Reitman, W. R. (1964) "*Heuristic Decision Procedures, open constraints and the structure of ill-defined problems*". In: M.W.Shelly & G.L. Bryan (Eds.) *Human Judgments and Optimality,* New York, Wiley.

Reynolds, C. (1987), "*Flocks, herds and schools: A distributed behavioral model.*", In: *SIGGRAPH '87: Proceedings of the 14th annual conference on Computer graphics and interactive techniques* (Association for Computing Machinery): pgs.25–34

Rittel, W.J. and Webber, M.M. (1973) "*Planning Problems are Wicked Problems"*, In: Cross, N. *Developments in Design Methodology*, London: Wiley Academy.

Ropohl, G. (1986). "*Information does not make sense,."* In: Mitcham and Huening (eds.). *Philosophy + technology II: information technology in theory.* D.Riedel Publishing. Dordrecht, DE

Sahal, D. (1986) "*Technological guideposts and innovation avenues*." In: *Research Policy*, Vol 14: Issue 61: pgs.61-82.

Scheurer, F. (2004) *"Turning the design process downside-up: Self-organization in spatial structures"* in: *CAAD Futures 2005*, Vienna: CAAD Futures

Scheurer, F. (2009) *"Architectural Algorithms and the Renaissance of the Design Pattern"* in: A. Gleiniger, G.Vrachliotis (Ed.): *Pattern,Ornament, Structure, Behavior*, Birkhäuser, Basel. 41-56

Scheurer, F. (2009) *"Size Matters: Digital Manufacturing in Architecture"* in: Abruzzo, E. et al. (Eds), *Dimension*. Vol. 12. 306090 Books: Princeton Architectural Press, New York pgs. 59-65

Schumacher, P. (2008) "*Engineering Elegance*" In: Hanif Kara (ed.), *Design Engineering AKT*, London 2008

Schumacher, P. (2009) "*Parametricism: A New Global Style for Architecture and Urban Design*" in: Neil Leach (ed.), *Digital Cities, Architectural Design,* Vol. 79, No. 4, pp. 14-23.

Schoch, O. (2003) *"Applying a Digital Chain in Teaching CAAD and CAAM"* in: *Digital Design: The Quest for New Paradigms: The 23rd eCAADe Conference Proceedings*. Lisbon, Portugal: 125-129

Schoen, D. and Wiggins, G. (1992) *"Kinds of Seeing and their Functions in Designing"*, in *Design Studies* Vol 13, Issue 2, pgs 135-156.

Sharples, Holden, Pasquarelli. (2003) *"Versioning: Evolutionary Techniques in Architecture"* In: *Architectural Design* vol 72 no. 5, London: Wiley Academy.

Shils, E. (1978) *"The Order of Learning in the United Sates from 1865 to 1920: The Ascendancy of the Universities".* In: *Minerva* Vol:16 (2). Springer Netherlands

Simon, H. A. (1973)*"The ill structure of ill-structured problems"*, In: *Artificial Intelligence* 4, pgs. 181-204.

Slessor, C. (2000) "*Material Witnesses"* In: *The Architectural Review*, Vol.207, Iss.43

Papell, C., & Skolnik, L. (1992). "*The reflective practitioner: A contemporary paradigm's relevance for social work education*." In: *Journal of Social Work Education*, Winter 1992. Issue28, vol.1, pgs.18-26

Sorkin, M. (2003), "Brand Aid, Or, The Lexus and the Guggenheim - Further Tales of the Notorious B.I.G.ness," Harvard Design Magazine 17, Fall 2002 / Winter 2003.

Speaks, M. (2000). *"How the New Economy Is Transforming Theory & Practice,"* In: *Arch. Record* (Dec. 2000): p.74

Stiny, G., Mitchell. W.J (1978) "*The Palladian grammar*." In: E*nvironment and Planning B*, vol. 5(1). Pion Ltd. London, UK: pgs.5-18.

Stungo, N. (2003) *"Dare to be Different: Why do Architects Strive to Use Unusual Materials"* , In: RIBA Journal, July 2003, no.70, pgs.24-26

Soar, R., Andreen, D. (2012). "*The Role Of Additive Manufacturing And Physiomimetic Computational Design For Digital Construction*" In: Menges, A. (ed) AD, Special Issue: *Material Computation-Higher integration in morphogenetic design*. Vol. 82, issue 2, 126-135. London: Wiley & Sons.

Tessmann, O. (2007) *"Structural Analysis as Driver"* In: *Surface-based Design Approaches*, International Journal of Architectural Computing: Issue 01, vol.6 pgs.19-23

Toshiko Mori, (2002) *"Immaterial / Ultramaterial"* in *Architecture, Design, and Materials*, Harvard Design School in association with George Braziller publishing, Cambridge, MA, pg.xvii.

Terzidis, K. (2007) *"The Etymology of Design: Pre-Socratic Perspective"* in: *Design Issues*: Volume 23, Number 4. Autumn 2007. MIT Press. P.69-78

Voyatzaki, M. (2009) *"Computing Architectural Materiality: The Hypernatural Aspirations of the New Paradigm",* In: *International Journal of Architectural Computing,* vol.7, no.4: 555-564

Weaver, W. (1948) *"Science And Complexity"* in: *American Scientist*, Vol 36: Issue 536, Rockefeller Foundation, New York City

West, M. (2008) "*Thinking With Matter*" In: Sheil, B. (ed.) *AD Protoarchitecture: Analogue and Digital Hybrids*. Vol 78, Issue 4, pages 50–55, July/August 2008

Willis, D. and Woodward,T. *"Diminishing Difficulty: Mass Customization and the Digital Production of Architecture,"* in *Harvard Design Magazine*, Fall / Winter 2006.

Wise, N., (1993). *"Mediations: Enlightenment Balancing Acts, or the Technologies of Rationalism"* in: Paul Horwich (ed.), *"World Changes: Thomas Kuhn and the Nature of Science"*. Cambridge, Mass.: MIT Press, 207-256.

Whitehead, H., Aisch, F. (2004) "*Specialist Modelling Group*" in: Beesley, Cheng, Williamson (eds.) *Fabrication: Examining the Digital Practice of Architecture, ACADIA 2004.* University of Waterloo, Cambridge, CAN.

Winner, L. (2004). *"Technologies as Forms of Life"* in: D. Kaplan (ed.) *Readings in the Philosophy of Technology*, Rowman + Litterfield: Lanham, MD.

Zaero-Polo, A. (2001) "*Roller coaster construction*" in: *Verb 1: processing*, Actar, Barcelona. P.13-15

Websites, internet articles & web references:

Ampère, A.M. (1822.): *Exposé des nouvelles découvertes sur l'électricité et le magneétisme*. Chez Méquignon-Marvis. Accessed at: http://books.google.ch/books?id=tBoAAAAAQAAJ [accessed: 12.11.2011]

Ampère, A.M. (1834): Essai sur la philosophie des sciences, ou, Exposition analytique d'une classification naturelle de toutes les connaissances humaines. Chez Bachelier. Accessed at: http://books.google.ch/books?id=j4QPAAAAQAAJ [12.11.2011]

Arayici, Y. et al. (2010) "*BIM Adoption and Implementation for Architectural Practices*" In: *Structural Survey*, Vol 29, issue 1. Emerald Group Publishing Limited http://usir.salford.ac.uk/13046/2/BIM_Adoption_and_Implementation_for_Architectural_Practices_Published_version.docx.pdf [16.02.12]

Balter, M. (2008), "Tool Use Is Just Another Trick of the Mind", in "Science NOW", January 28, 2008, http://news.sciencemag.org/sciencenow/2008/01/28-02.html [28.05.2011]

Bánáthy, B.H. (1997). *"A Taste of Systemics"*, The Primer Project: http://www.newciv.org/ISSS_Primer/asem04bb.html [14,05.2007] p.22

Blum, A. (2007) *"Plug+Play Construction"*. In: *Wired,* January 2007, www.wired.com/wired/archive/15.01/home1.html [18.05.2009]

Burnham, J. (1968) *"Systems Esthetics"*. In: *Artforum*. Issue: September, 1968: Accessed at: http://www.arts.ucsb.edu/faculty/jevbratt/readings/burnham_se.html [02.09. 2010]

Chimero, F. (2010) *"The shape of design"*. Accessed at: http://vimeo.com/17084347 [08.10.2010]

deBotton, A. (2007) *"On The Aesthetics of Architecture". A*udio interview as part of the *"Philosophy Bites"* series: http://traffic.libsyn.com/philosophybites/DeBotton1.MP3 [08.07.2008]

Eames, C,. Eames, R., IBM Corporation (sponsor) (1958) *"The information machine."* Video for the 1958 IBM pavilion: http://www.youtube.com/watch?v=dA_Wpx8KHOw [12.10.2010]

Eastman, C. (2009) *"What is BIM?"* Digital Building Lab @Georgia Tech: http://bim.arch.gatech.edu/?id=402 [17.11.2011]

"GeneratorX – Art from Code" Webpage dedicated to the use of programming as a basis for design. http://www.generatorx.no/tag/rhinoscript [18.09.2009]

Goldberger, P (2004) *"Does Architecture Matter? Thoughts on Buildings, Design, and the Quality of Life," Fixed Income Forum,* Chicago, March 25, 2004. http://www.paulgoldberger.com/lectures/10 [10.06.2010]

Hall, A. Rupert, (1962) "*The Changing Technical Act*", in *Technology and Culture*, Vol. 3, No. 4, Autumn 1962. Pgs. 501-515. Accessed via: http://www.jstor.org [12.10.2010]

Hall, P, "*Living for Tomorrow*,"in: *Metropolis,* December 2002, [11.06.2010] http://www.metropolismag.com/html/content_1202/mit/index.html

Kelly, K. (2012). "New Rules for the New Economy" at: http://www.kk.org/newrules/blog/2012/05/why-cant-a-machine-do-this.php [02.05.12]

Kolatan, S. and MacDonald, W. *"KOL / MAC Architects, Venice Biennale International Exhibition"* in: *Archilab*: www.archilab.org/public/2000/catalog/kolata/kolataen.htm [12.04.2009]

Landt, J. (2001) *"Shrouds of Time, the History of RFID,"* in: *The Association for Automatic Identification and Data Capture Devices,* www.aimglobal.org/technologies/rfid/resources/shrouds_of_time.pdf [12.05.2009]

Liukkonen, P (2008). "Vitruvius (fl. 46-30 B.C.E.)": http://www.kirjasto.sci.fi/vitruv.htm . [14.12. 2010]

Mashelkar, R.A. (2010) "*Breakthrough designs for ultra low-cost products*." TED talks: http://www.ted.com/talks/r_a_mashelkar_breakthrough_designs_for_ultra_low_cost_products.html [02.11.2010]

Mau, B. (2007). *"What is Massive Change?"* http://www.massivechange.com/about [12.02.09]

Mraz, S.J. (2009) *"Changes in the Engineering Profession Over 80 Years"* In: *Machine Design*. April, 2009. Accessed at: http://machinedesign.com/issue/2009-04-09 [10.02.2010]

Newman, W. M. (1966) *"An Experimental Program for Architectural Design*", in *Computer Journal,* vol.9, Issue 1. Oxford Journals. Pgs. 21-26. Accessed at: http://comjnl.oxfordjournals.org/content/9/1/21.full.pdf [10.05.2009]

Nilsson, F. (2007) *"Design, rhetoric, knowledge: Some notes on grasping, influencing and constructing the world".* In: Ullmark, P., et al. (eds.) *"Proceeding from the Nordic Design Research Conference: Nordes07"* accesed at: http://www.nordes.org/data/uploads/papers/99.pdf [12.04.2010]

Oxman, R.M., Oxman, R.E. (1991) "Refinement and Adaptation: Two Paradigms of Form Generation in CAAD." CAAD futures Digital Proceedings: my.arch.ethz.ch/sspycher/AKAD/CF'91/20_OxmanRTF.doc [22.05.2010]

Postman, N. (1990) "*Informing Ourselves to Death*": Text of a speech given at Gesellschaft fuer Informatik, in Stuttgart, October 11, 1990. http://www.mat.upm.es/~jcm/postman-informing.html [16.11.2010]

Rosengren, M. (2008) "*The Cave of Doxa – Reflections on Artistic Research and on Cave Art*" In: *Art Monitor*, vol. 4. Göteborg University, Göteborg Sweden. http://gupea.ub.gu.se/bitstream/2077/21776/1/gupea_2077_21776_1.pdf [21.04.2010]

Rutan, D. – "Reconstructivism" Resource and example page for parametric Rhino scripting http://www.reconstructivism.net/ [21.09.2009]

Schumacher, P. (2008) "*Parametricism as Style - Parametricist Manifesto*". Self published at: http://www.patrikschumacher.com/Texts/ [21.11.2011]

Seletsky, P. (2005) "Digital Design and the Age of Building Simulation." AECbytes Viewpoint #19: http://www.aecbytes.com/viewpoint/2005/issue_19.html [17.11.2011]

Silver E. (2007), "*GSA to Require Building Information Models*," Engineering News Record, http://enr.construction.com/news/informationtech/archives/050121.asp [12.09.2009]

Smith, M. K. (2001) 'Donald Schön: learning, reflection and change', the encyclopedia of informal education, http://www.infed.org/thinkers/et-schon.htm, [16.04.2009]

Smuts, J. (1927). *"Holism and Evolution"*. London: McMillan and Co Limited. Accessed at: http://www.archive.org/stream/holismandevoluti032439mbp#page/n7/mode/2up [25.04.2010]

Sylvester , M. "FabPrefab - Designer prefabrication of buildings and homes" www.fabprefab.com [12.09.2008]

Taggart, S. (1999) "The 20-Ton Packet," in: *Wired,* October 1999. http://www.wired.com/wired/archive/7.10/ports.html [17.02.2011]

Turing, A.M. (1950) "Computing Machinery and Intelligence" in Mind vol. 49. Pg.433-460 Accessed at: http://cogprints.org/499/1/turing.html [22.04.2010]

Tuck, M (2010) "Gestalt Principles Applied in Design". On: *Six Revisions* (web-blog) http://sixrevisions.com/web_design/gestalt-principles-applied-in-design/ [02.12.2011]

Weiser, M., Seely Brown, J. (1996) *"The Coming Age of Calm Technology",* Xerox PARC: http://www.cs.ucsb.edu/~ebelding/courses/284/papers/calm.pdf [14.07.2009]

Wengenroth, U. (2000) *"Science, Technology, and Industry in the 19th Century".* Munich Center For The History Of Science And Technology. Munich, DE (*working paper*). http://www.mzwtg.mwn.de/arbeitspapiere/Wengenroth_sci-tech-ind-19c.pdf [17.11.2011]

Zaero-Polo, A. (2000) "*FOA, Code Remix 2000*", 2G, No.16: Nexus http://ds13.uforg.net/wp-content/uploads/2009/10/FOA_Code_Remix2000.pdf [04.12.2011]

Referenced Dissertations and Theses:

Baljon, C. (1990) The Structure of Architectural Theory: Study of Writings by Semper, Ruskin, Alexander . Dissertation, Technical University of Delft. TR Diss 2223.

Besson, A. (2009) Stratégie versus composition, PhD Dissertation, EPF Lausanne, Nr.4205

Buri, H. (2010) Origami - Folded Plate Structures, PhD Dissertation, EPF Lausanne, Nr.4714

Dooley, S. (2004) The Development Of Material-Adapted Structural Form, PhD Dissertation, EPF Lausanne, Nr.2986

Dorst, C.H. (1997) Describing Design: A Comparison of Paradigms, PhD Thesis, Delft: Delft University of Technology.

Dritsas, S. (2004) Design Operators. Masters of Science in Architecture Studies, Massachusetts Institute of Technology, June 2004.

Gow, M. (2007) Invisible environment: art, architecture and a systems aesthetic, 1960-1971. PhD Dissertation, ETH Zürich, Nr. 17220

Kilian, A. (2006) Design Exploration through Bidirectional Modeling of Constraints, PhD Dissertation: Massachusetts Institute of Technology, February 2006.

Oxman, N. (2010) Material Based Design Computation, PhD Dissertation: Massachusetts Institute of Technology, June 2010.

Page, J. (2007) Simulating Occupant Presence and Behaviour in Buildings, PhD Dissertation, EPF Lausanne, Nr.3900

Schindler, C. (2009) *Ein architektonisches Periodisierungsmodell anhand fertigungs-technischer Kriterien, dargestellt am Beispiel des Holzbaus.* PhD Dissertation, ETH Zürich, Nr.18605

Stotz, I. (2009) Iterative Geometric Design for Architecture, PhD Dissertation, EPF Lausanne, Nr.4572

Strehlke, K.(2008) Das Digitale Ornament in der Architektur, seine Generierung, Produktion und Anwendung mit Computer-gesteuerten Technologien. PhD Dissertation, ETH Zürich, Nr.17830

Sutherland, I (1963) Sketchpad: A man-machine graphical communication system, PhD Dissertation: Massachusetts Institute of Technology, June 1963.

"To be realistic one must always admit the influence of those who have gone before."

(1972) Charles Eames, Quoted in: The Films of Charles & Ray Eames, notes.

List of figures

Chapter 2. Thesis

Chapter 3. Technology

Chapter 4. Theory

Chapter 5. Investigations

Chapter 7. Discussion

Apendix:

Appendix 01: Industrial ages and revolutions.

Technology and the evolution of civilization: Ages and Revolutions

- Stone age: 3000 BC

- Bonze age: 3000-1000 BC

- Iron age: 1000 BC – 400 AD

- Middle ages: 400-1400AD

- Renaissance: 1400 – 1700 AD

- Enlightenment: 1650 – 1800 AD

- Industrial revolution: early 1800's

- Technological revolution: later 1800's -1920

> World War 1: 1914 – 1918

- Evolution of mass productions 1920-1930's

> World War 2: 1939 – 1945

> ENIAC: 1946. The first general purpose programmable digital computer.

- Nuclear age: 1950's

- Electronics age: 1960's

> Birth of modern computing: 1971

> Mainframe e-mail

- Computing revolution: 1980's

>World Wide Web:1989

- Information age: 1980-2000's

Appendix 02: The Industrial Revolution

"The industrial revolution created not just consumers but a consumer society. The digital revolution has created alongside personalized and highly tailored access to information (and the ability to disseminate data), the expectation of individualized and meaningful experiences."

Brown, T. Katz, B., (2009) *Change by Design.*

The rise of modern industry has been dominated by the concept of mass production. The capability to produce at new scales was driven by new knowledge of production, new understanding of optimization of processes, the availability of new forms of energy, and the ensuing development of new materials and material methods. The combination of all of these factors changed the balances of time, investment, labour and productivity in the development of industry. But the fundamental question is: What came first? What was the root motivator for the changes that eventually led to mass industrialization?

The positivistic school of thought in the 1950s and 1960s, believed that industrial technology was "applied science", and that technological innovation was the direct result of putting scientific research to work. In 1962 A. Rupert Hall declared:

"The late eighteenth century was the point in time at which the curve of diminishing returns from pure empiricism dipped to meet the curve of increasing returns from applied science. This point we can fix fairly exactly, and so we may be sure that if science had stopped dead with Newton, technology would have halted with Rennie. The great advances of later nineteenth century technology owe everything to post-Newtonian science."[1]

In investigating the relationship between design and industry, and between science and technology it is tempting to take a single perspective of a "push-hypothesis," whereby science pushed technology, which in turn pushed design and industry towards innovation[2]. This linear model is however simple and lacks a complexity that addresses the interrelatedness of the components.

Historical investigators[3] now question the conventionally held idea of technology being subservient to science (as applied science), and now regard technological development as a quasi-independent field, one more related to the industrialists and shop floor technicians than related to scientists. In accepting this more complex, but realistic flow of innovation, we are able to see how experience and "hands on" intuition (of craftsmen, technicians, and entrepreneurs) was an equal driver of both industrialisation, and also for design.

When looking at innovation, the relationship of science and technology cannot be seen as one of epistemological hierarchy, but rather should be seen as having a systemic but complex interrelatedness. This association is also not to be taken in isolation, but needs to include the similar symbioses of industry and design. If, on the other hand, we conceive of the state of innovation as a four part intersection of science, technology, design and industry, the result is a more complex and a much more plausible pattern of multidirectional influences; to and from each of the elements.

[1] Hall. (1962) "The Changing Technical Act," p.511.

[2] From: Wise, "Mediations," 253; and Shapin and Shaffer, Leviathan and the Air Pump , p.25.

[3] Wengenroth (2000), C.W. Bernhard (1991), Paulinyi, A, (1991).

> *"Diesel always acknowledged that intuition rather than "science" had been the main source for his invention. Science played an important role in directing his curiosity and testing the consistency of his reasoning, but it did not translate directly into technology; however, there is no account of Linde's refrigeration process or the Diesel engine that can avoid crucial information from science."*[4]

The reality of motivating factors for development, as Akos Paulinyi[5] has shown, is actually somewhere in-between science and industry. "Process engineering" (an unknown field at the time of the Industrial Revolution) became the backbone of industrial development. Design and innovation were rooted in the skills and experience of machinists, production engineers, and factory managers; those who had the better insight for "pull" or demand-driven reasons for development, and those who would most profit from the implementation of innovation.

In the initial implementation of new technologies, new machines, and new scientific knowledge of the scientists and engineers drove innovation and how it was to be implemented. However soon thereafter, practitioners with their knowledge of "real world" issues re-established (an evolved version) of the shop>school hierarchy. It was industry that recognized that machine tools and heavy machinery production enabled an amplification loop; a form of *autopoiesis* where new machines enabled new capability, and this in turn enabled new machines.[6] Machining tools were of paramount strategic importance for the autonomous development of industry, and access to the machines represented the access to new practical knowledge. Machining represented the only technology that could be employed to replicate itself and at the same time it provide the tools for other forms of production. Machine tools were a form of perpetual industrialization, but they were also key to the evolution and innovation in machine making.

Industries recognized the value of their own knowledge and production capabilities, and as such were empowered to make demands for specified scientific research. The areas of investigation; such as new material science, new material-forming processes, energy management, distribution, and transformation were all identified as "enablers": knowledge that was traditionally outside of the scope of industry, but whose development in science enabled a revolution in technology that pushed the industrialization of Europe and North America.[7]

The ensuing emergence of engineering theory did enable a new era of science-technology feedback. It was not, however, simply science being adopted by engineering in ever more fields; it was also engineering developing its own scientific approaches, and making research demands back into the pure science fields of material and energy research.[8] It was scientists, and their skills for objective measuring, testing, and evaluating properties, that made science indispensable for industrial enterprise, and materials testing became one of the major fields of employment for scientists.[9]

A reductionist view of the industrial revolution as an epitomization of accelerated scientific technological progress is no longer defendable. The development of civilization in this time is dependent on factors, which extend beyond the range of science, technology, design and industry. While it is clear that this evolution of this time would have been significantly different without technical innovations, the parameters of influence should be acknowledge to equally include politics and socialism, communications, economics, secularization, and culture.

---

[4] Wengenroth, Science, Technology, and Industry in the 19th Century, p.27

[5] Paulinyi, (1986) "Revolution and Technology."

[6] Dienel. Ingenieure zwischen Hochschule und Industrie , chap. 5.

[7] Paulinyi, (1986) "Revolution and Technology."

[8] Paulinyi, (1982) "Technologietransfer," 128-129.

[9] Livesay, Andrew Carnegie and the Rise of Big Business, 114.

The historiography of the relations of nineteenth-century science, technology, design, and industry has shown that science was but one instrument for innovation, and certainly not the most important one. Understanding interrelatedness of all factors including organization, craft knowledge, tinkering, and building on existing experience all together constituted more productive momentum of industrial growth than science.

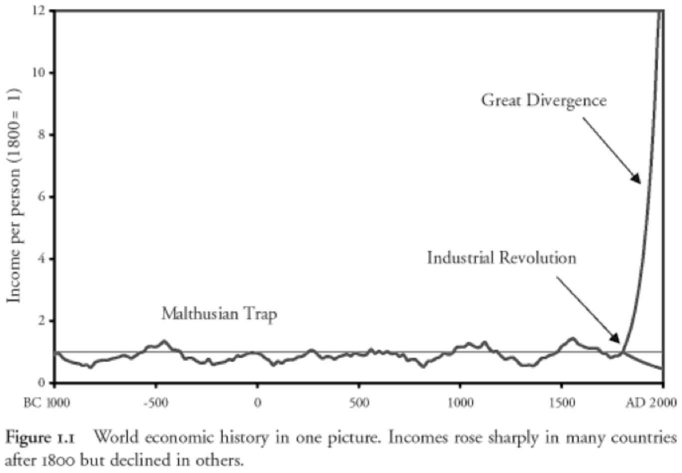


*Fig. A3.1a. Adjusted percapita income as a function of time demonstrating the Malthusian Trap – pre industrial revolution. The industrial revolution changed average income for a minority of the population, wheras for for the majority their overall spending power decreased. (source: Clark, G. (2007) "*A Farewell to Alms: A Brief Economic History of the World*": 43.)*

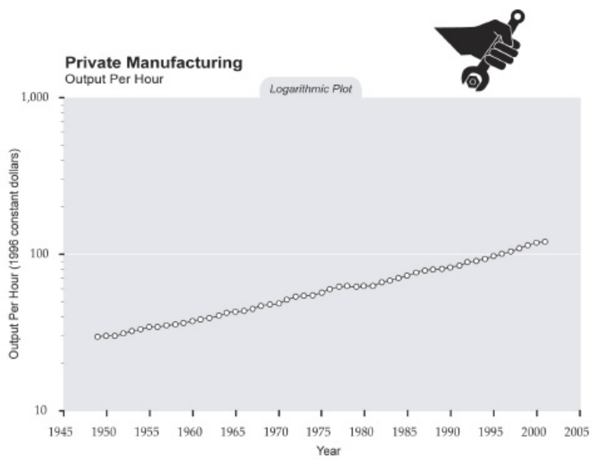


Fig. A3.1b. Logarithmic graph of manufacturing productivity in USA since 1945. The logarithmic nature of the slope indicates massive advancement of production and technological capability. (source: http://www.singularity.com/charts/page101.html)

Economist Thomas Malthus has demonstrated that historically, the estimated average income was held in equilibrium as technological advances typically resulted in population growth (and wider distribution of resources rather than improvements to standards of living). The Industrial Revolution was a fundamental paradigm-shift to this theory, in that the income per person dramatically increased (in some countries), and they broke out of the "Malthusian Trap". The modern productivity graph clearly shows the relation between scientific, technological, and design innovations, and how they have caused fundamental industrial, societal, and cultural change.

Appendix 03: Cellular Automata

Cellular automata is a concept for dynamic computational digital models. The concept develops complex behaviour from a very simple set of rules when a system is evaluated repeatedly in an iterative method. Cellular Automata were conceived of in 1940 by Stanislaw Ulam and later developed by von Neumann and Weiner

As a spatial and dynamic system the principles of cellular automata are based on five basic concepts: a unit cell, the state of that cell, The cell in a matrix of cells, the state of the neighbours to a specific cell, and the transition rule that is applied to a cell.

The cells in a cellular automaton are all the same, and are arranged in an n-dimensional space, typically a two-dimensional grids (although theoretically this can be multi-dimensional space). The cells have a discreet state which is dictated by the transition rule, and which is defined by the states of the neighbouring (edge or corner connected) cells. The system is a dynamic and iterative system, so that the entire grid (ecosystem) is recalculated for each instance of time (t). In addition, with each iteration a "mutation" is introduced in the system, (either as a new random cell, a sexual combination of cells, or a algorithmically derived mutation cell). The result of this is the revaluation of the entire grid with each iteration, however because each cell is affecting multiple neighbours, the cascading of influence creates complex interrelationships.

The best known implementation of this concept is the "Game of Life", introduced by John Conway in 1970. Conway's method was simplified as a two-dimensional matrix, where the cells have one of two states: alive or dead. There are only three transition rules: A cell with exactly three live neighbours becomes alive in the next iteration. Living cells with fewer than two living neighbours die in the next iteration. Living cells with more than three living neighbours die also in the subsequent generation.

There are several potential applications for cellular automata in architecture and urbanism. They are used primarily for growth and traffic simulations used to study dynamic processes. Can produce in the field of ornamentation with this computer model in simple and complex patterns especially dynamic patterns.

Appendix 04: Technology in Practice: examples

It is recognized that architectural practices evolve. As such the inclusion of examples of current architectural practice is temporal and project specific. Over the course of this thesis, through investigation, interview, and discourse, the following offices have been identified as using specifc working methods and their relation to technology. This list is included for reference and elucidation.

Architectural practice

Comprehensive users

The practices use digital tools at a high level of expertise, but it is not a primary driver for design strategies. For complex computational needs, external consultancy is sought.

- Renzo Piano Building Workshop (ex: P+K Cloppenburg, Köln, Paul Klee Zentrum, Bern)
- UN Studio (Mercedes Museum, Stuttgart;)
- Studio Daniel Libeskind (ex: Futuropolis, St. Gallen)

Professional research and development groups

Specialized internal technology groups as independent teams that cooperate and guide designers during development.

- Foster and Partners – Specialist Modelling Group
- Gehry Partners - Gehry Technologies
- ONL – Kas Oosterhuis

Integrated offices

Integrated offices are architectural firms that have dedicated their working methodology to include direct feedback from production and construction in the design method.

- SHoP - Shaples Holden and Pasquarelli Architects, New York.
- Greg Lynn Form, Architecture and Interior design, Venice Beach, CA.
- Heatherwick Studios, Design and production studio, London, UK.

Architectural Consultancy

In situations and projects where the "in office" skills of geometry, computation, or other specific requirements are not adequate, there are alternate consulting sources for expertise.

Engineering offices

Professional engineering firms now have digital design and production support groups.

- Ove Arup & Partners - Foresight and Innovation Group
- Buro Happold
- Bollinger + Grohmann
- AKT: Adams Kara Taylor Engineering

Specialized consultancy

Commercial consultancy with expertise in specific design or production areas:

- Design to Production – Geometry and production consultants, Zurich.
- Evolute – geometry consultancy, Vienna.
- Gehry Technologies, various locations.

External Consultancy

Fabrication services

Hybrid research groups

Hybrid research groups are entities that are a collaboration of players. There are three prime examples for hybrids that are currently having an impact in the architectural profession:

- Smart Geometry Group: A collaboration and support platform for researchers, practitioners, and educators focused on parametric design and production technology. This platform is sponsored by the Bently through their software Generative Components (GC). The Smart Geometry Group is composed of academic and professional architects, and its main function is to teach GC workshops and hold conferences. (http://www.smartgeometry.com/tech.htm).

- Fab Lab: An initiative set up by Prof. Neil Gershenfeld, to research how the implementation of digital fabrication equipment in different contexts would enable "common" people to become designers and producers. The research is a project of the MIT Centre for Bits and Atoms, and now engages experts from fields of design, manufacturing, electronics, mechanics, and other technical fields. (ref: http://fab.cba.mit.edu/)

Appendix 05: General recurring observations

The following are general observations were made over multiple cycles of teaching and investigation. These observations are personal and are in no way empirical or objective. They have been retrieved from course notes and the records from students. They are intended to support the findings made concerning learning and aptitude, and are stated here for reflection and insight purposes only and do not reflect any verifiable conclusion method.

- Differences of creative aptitude and talent influence the abilities in technology. In general those students with more intuitive creative or artistic talent, struggle with learning technology. Those students who are accustom to "working a problem" to achieve success in design, are also more apt to be able to adapt to technology constraints.
- Artistically talented practitioners are better able to understand abstract relationships between desperate issues. This is specifically interesting in relation to explaining parametric programming and relational associativity
- Intuitive designers do not create more conceptual work after they have overcome the learning curve for technologies. Intuition with architecture does not seem to translate to conceptualizing in technological media.
- Practitioners who show experience with maths, logic and science do show more aptitude to creative use of technologies after they have overcome the learning curve.
- Analytic methods reinforce the use of digital technologies. If a tool is used to quantitatively then designers will invest into its use. When tools are to be used qualitatively then there is a tendency to question it. A method to resolve this is to formulate abstract objective goal states for subjective tasks.
- Programming and simulation have very steep learning curves, but also slow satisfaction return. This is directly attributed to the heavy initial investment in learning, and also the detailed and intricate set-up of a initial structure, with very little intermediate feedback.
- Learning "too many" technologies at the same time is problematic. It is best to reduce the learning to serial approach. This is especially difficult when the designers themselves are not confident in their design skills (still exploring the practice of design methods).
- The success of "exploratory" modes of investigating design opportunities, options and methods was directly proportional to the comfort the practitioner had with the tools.
- The comfort with machines and tools also translated into comfort with fabrication equipment, although the basic learning curve was less steep due to the reward structure of production.
- Practitioners could conceptually understand the advantages of associativity however in architecture, where each project is (conceptually) unique, there was resistance to the work investment required to making project tools.
- There was an overall resistance to using text based programation, the hesitance was lessened with the use of visual scripting (Grasshopper). This is attributed to the analogous relation of graphical methods to the diagramming methods of design learning.
- There is no conclusive correlation (pro or con) between artistic intuition and abilities and proficiencies with production machines.
- Practitioners who are more objective in their character tend to make additional efforts to understand the techniques and parameters of the production machines, resulting in better comprehension (but not necessarily exploration) of their fabrication potentials.
- The direct "data relationship" between design and production can be understood as a series of "creative opportunities". Practitioners who understand this digital associativity in parametric design, tend to be able to exploit the digital-physical linkages better.

Appendix 06: List of student practitioners

ETHZ

AS02
Berkowitsch, Philip
Haehnel, Roland
Heberie, Matthias
Hesse, Christoph
Hüssner, Karina
Jackowska, Katia
Majerus, Michéle
Parthier, Sebastian
Prinz, Nikolas
Postelnicu, Alex
Weber, Anina
Zantman, Bart

SS03
Nele Dechmann
Daniela Heyland
Gunter Klix
Elena Kohl
Rebecca Lehmann
Marceline Ruckstuhl
Sylvia Schaden
Laura Schneider
Martien Schoep
Max Simmendinger
Simon Zimmermann

Eternit Ornament
Chiara Castellan
Raul Castano
Matthias Heberle
Eunho Kim
Samuel Lauber
Irène Leuthold
Alexander Schmiedel
Sinem Tunakan
Bettine Volk

AS03
Michael Bölling
Clara Fornens
Lorenz Lachauer
Jurgen Stoppel
Max Boerenger
Michael Kren
Svenja Rausch
Thomas Kremple

SS04
Birgit Koenig
Flavian Lekkas
Johannes Schmersahl
Paola Peralta
Jonathan Tramba
Isabella Gerster
Victoria Easton
Martin Henn
Alexandro Buehl
Stephanie Marti
Viera Bakic
Tanjo Kloepper
Martin Kostelezky

AS04
Ingmar Kurtz
Carolina Mojto
Felix Siegrist
Jörg Hillesheim
Christina Ringelman
Mathias Bernhard
Dominique Meier
Simone Renfer
Vanessa Borkmann
Johann Reble
Jonas Grob
Anna Flueckiger

SS05
Stephan. Albrecht
Miriam. Hochuli
Till. Kamp
Michael. Knauss
Silvan. Oesterle
R. Scherrer
Lukas. Sonderegger
Sabine. Walker
Jenny. Weiss
Karen. Zech
Markus. Giera

EPFL

SS08
Julien Ayer
Tomas Kral
Martin Oberhauser
Valerian Gagnaire
Thomas Austerveil
Isabella Pasqualini
Nikolaj Friis
Anne-Chantal Rufer
Germain Brisson
Jonathan Montandon
Wynd van der Woude
Victor Løvetand Julebæk

AS08
Sara Albrizzi
Henrik Axelsson
Cristina Bellini
Eglantine Bigot
Alberto Fiore
Godet Linus
Lluis Gratacos Ginjaume
Melanie Hammer
Claudia Jäkel
Ossi Konttinen
Isabelle Nour
Stefanie Reinke
Paloma Lara Rodrigo
Caroline Schmidt

SS09
Natacha Bauer
Arnaud Bovet
Laura Blosser
Miya Buxton
Dorothee Fritzsche
Tamara Henry
Emma Jonsson
Vincent Lucas
Katrin Marweld
Leon Meyer
Nina Otren
Raphaël Perrinjaquet
Svend Reymond
Nanna Riise

SS10
Didier Callot
Franck Dal-zotto
Alexandre Endress
José Pedro Faria Azevedo
Stephane Grandgirard
Vincent Mermod
Mobasher Niqui
Martin Nordah
Hildur Ottósdóttir
Julie Riedo
Fanny Sernhede
Toru Wada
Livia Wicki
Linda Wiksten
Martin Wyss

AS10
Francesco Borghini
Germaine De Bazelaire
Meriton Demukaj
Nathalie Egli,
Marco Ferarri
Patrizia Gabrielli
Shun Horiki
Mélanie Huck
Aurélie Krotoff
Andrés Tovar Nuez
Chloé Rivière
Stefan Uhl
Martina Vesik
Jeanne Wellinger

SS11
Campaci Giovanni
Florindo Eva
Jiménez Díaz Eva
Marquis Pierre
Rodrigues Maria Inês
Di capua Davide
Krieger Benjamin
Loock Jakob
Mato sabat Marta
Philippe Edouard
Yang Sizhou

Appendix 07: Class Surveys

For each course given, all participants were required to complete an initial survey. This was initially done so as to gauge the level of proficiency within the students in the course, and also to prepare for specific technological issues. As the courses progressed the survey became defined and consistent from semester to semester, providing some basic (un-objective) statistical data for the courses. The surveys were started with teaching at the ETHZ in 2003.

Below are the two typical surveys as provided to students.

Entry Survey

NAME:

E-MAIL:

EPFL STUDENT (if no, then where from: school and program)

WHAT TYPE OF LAPTOP COMPUTER DO YOU OWN?

WHAT CAD PROGRAMS DO YOU KNOW OR WORK WITH?

RATE YOUR COMFORT LEVEL WITH 3D CAD MODELLING SOFTWARE:

1. unfamiliar
2. limited working knowledge
3. good working knowledge
4. advanced working knowledge
5. professionally proficient

DO YOU HAVE ANY PROGRAMMING EXPERIENCE?

1. None
2. Limited knowledge
3. Experience with some form of programming
4. Working knowledge of programming, some CAD specific scripting
5. Comfortable with CAD specific scripting

DO YOU HAVE ANY EXPERIENCE IN CONSTRUCTION OR BUILDING? (if yes, in what capacity)

DO YOU HAVE ANY CAM SOFTWARE OR DIGITAL FABRICATION MACHINE EXPERIENCE?

1. None
2. Limited knowledge (ex: prepared files for the laser or Zund in the AM)
3. Experience (ex: operated the laser or Zund in the AM)
4. Experience with digital fabrication at larger scales
5. Professional experience with digital fabrication and building projects.

DO YOU HAVE ANY OTHER "DIGITAL SKILLS" ASSOCIATED TO ARCHITECTURAL DESIGN?

(rendering, animations, simulations, engineering analysis, …)

WHAT IS YOUR PROFESSIONAL EXPERIENCE IN ARCHITECTURE?

(stage, office year work, competitions, … if yes, then at which practice?

Upon the creation of the DD+P course, a second survey was incorporated into the course methodology, to collect data at the end of the course. This survey is used to determine the effectiveness of the teaching, and the progress of "general knowledge" as the technology was becoming more ubiquitous.

Exit Survey

NAME:

RATE YOUR CURRENT LEVEL OF EXPERIENCE WITH 3D CAD MODELLING SOFTWARE:

1. unfamiliar
2. limited working knowledge
3. good working knowledge
4. advanced working knowledge
5. excellent working knowledge

RATE YOUR CURRENT LEVEL OF EXPERIENCE WITH SCRIPTING: (or Grasshopper)

1. Poor
2. Limited
3. Good
4. Able to develop projects on my own
5. Able to use scripting across different tools

RATE YOUR CURRENT LEVEL OF EXPERIENCE WITH DIGITAL FABRICATION: (which machine?: ________)

1. Still scary
2. Comfortable but still need help and supervision.
3. Comfortable.
4. Able to operate the machine on my own, but need digital preparation help.
5. Able to fully use the machine on my own.
6.

DO YOU FEEL THAT YOUR SKILLS HAVE IMPROVED IN OVER THE SEMESTER?

DO YOU FEEL THAT YOU ARE MISSING SPECIFIC DIGITAL SKILLS NOT COVERED IN THE COURSE?

DO YOU FEEL THAT YOU HAVE A GOOD UNDERSTANDING OF THE DIGITAL CHAIN?

WILL YOU CONTINUE TO USE SCRIPTING OR PROGRAMMING IN YOUR DESIGN WORK?

WILL YOU CONTINUE TO USE DIGITAL FABRICATION IN YOUR DESIGN WORK?

CV: Russell Alexander Loveridge

Current Occupation:

Manager Sustainable Technology: Holcim Foundation for Sustainable Construction — Zurich, CH

Education:

2006 - 2012	**Doctorant**, lapa – Swiss Federal Institute of Technology. EPFL	Lausanne, CH
2000-2001	**MAS.Arch, NDS Dipl.Arch CAAD** – ETH Zürich.	Zürich, CH
1996-2000	**B.Arch (Hon)**, Architecture - University of Toronto	Toronto, CAN

Employment history:

2005-Present	Digital design, fabrication, and construction consulting *Professional Consulting*: Digital design, CAD, fabrication, construction process design.	Zürich, CH
2005-2011	lapa – Laboratoire de la production d'architecture: EPFL Lausanne *Research Director, Course Director: Digital Design and Production.*	Lausanne, CH
2002-2005	Chair of Maschinic Process in Architectural Design: ETH Zürich *Dotzent:* Responsible for the chair, courses, research projects, and administration.	Zürich, CH
2001-2002	Maschinelle Prozesse und Darstellungtechniken im Entwurf: ETH Zürich *Assistant to:* Guest Professor Gregg Lynn, Marcelyn Gow	Zürich, CH
2002	Perspectix AG, Zürich – Digital Design *CAAD construction modelling:* Database, interface design and programming.	Zürich, CH
2000-2001	ORL – Institute für Ort, Raum und Landschaftsentwicklung, *Research Associate:* Research urban modelling and sustainable land management	Zürich, CH
2000	Dutoit, Alsopp, Hillier: Architects and Planners *Project Architect:* large scale mixed use residential-commercial development:	Toronto, CA
1998-2000	CLR – Centre for Landscape Research, University of Toronto *Research Associate:* Digital Landscape and urban modelling CAAD and GIS programming, development of urban planning	Toronto, CA
1991 - 1997	Sustainable Buildings Group: CanMET - (contract) Canadian Centre for Material and Energy Technologies, Ministry of Natural Resources Canada Sustainable Buildings Group: Advanced Houses Program	Ottawa, CA

Extracurricular:

2011	External Examiner: IAAC – Open Thesis Fabrication Program Institute for Advanced Architecture of Catalonia	Barcelona, ES
2009	Organiser and Technical Chair - ACADIA 2009 Conference: *"reForm()"* Organizing chair for the ACADIA conference at the School of the Art Institute of Chicago.	Chicago, USA

Publications:

2011	"Parametric Materiality" CAADRIA Conference 2011: *"Circuit Breaking"*	Newcastle, AUS
2011	"The Digital Design Paradox" Book Chapter: *"e-Motion"* exhibition and symposium	Vienna, AT
2010	"Fantastic Form: Digital Design as Fiction and Fact" Swiss Design Network conference 2010: *"Design Fictions"*	Basel, CH
2009	ACADIA 2009: reForm( ) Building a Better Tomorrow. Sterk, T., Loveridge, R., Pancoast, D., (eds). *"Proceedings of the 29th Annual Conference of the ACADIA*. SAIC: School of the Art Institute of Chicago. ISBN: 978-0-984270507	Chicago, USA
2006	"The Digital Ornament using CAAD/CAAM Technologies" * In: *IJAC - International Journal of Architectural Computing*, Volume 4, No 1; January 2006. pp. 3	
2006	"Parametric Design: Mass Customization Concepts in Architecture" *MCPC06: Converging Mass Customization and Mass Production:* HKST.	Hong Kong
2005	"The Redefinition of Ornament: Programming and CNC Manufacturing"* *CAADfutures Conference 2005.* Vienna University of Technology	Vienna, AT

* papers co-authored with Dr. Kai Strehlke

Recent presentations:

2011	RIBA Symposium: University of Liverpool: "Smart Materials in Architecture" Keynote Speaker: *"Parametric Materiality"*	Liverpool, UK
2011	Institute of Advanced Architecture of Catalonia: IAAC. Invited Lecture: *"Digital Sustainability"*	Barcelona, ES
2011	CAADRIA Annual Conference "Circuit Breaking" Presenter and Conference panel moderator: University of Newcastle	Newcastle, AUS
2011	École Special d'Architecture (ESA) Paris Invited Lecture: *"Logical building"*	Paris, FR
2011	Technical University Vienna (TU Wien) Invited Lecture: *"The Digital Design Paradox"*	Vienna, AT
2010	Fachhochschule Nordwestschweiz: Institut Design und Kunstforschung Invited Lecture: *"Fantastic Form: Digital Design as Fiction and Fact"*	Basel, CH
2010	Bahrain International Forum for Architecture Keynote Speaker: *"Alien Architecture: Globalization + Architecture in the Gulf"*	Manama, BAH

Professional design and fabrication projects:

2010	Fischer Reinach, renovation of commercial office space Digital fabrication consulting: Blättler Dafflon Architects	Zürich, CH
2007	Peka Systems AG: Ornamental Interior panel system Digital fabrication consulting: Ralph Blättler, Architects	Lucerne, CH
2005	Schweizerische Landesmuseum: Ornamental Doors Digital fabrication consulting + design collaboration: Christ + Gantenbein Architects AG	Zürich, CH
2004	Schweiz Nationalbank: Façade and exterior door system Digital design and fabrication consulting collaboration: ARC Architects.	Zürich, CH