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THE AESTHETICS OF TOPOLOGY OPTIMISATION AND NON-STANDARD ANALYSIS

Master Thesis explanatory document
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Abstract

Over the last few years, architects have been given access to a myriad of new generative tools that are unprecedented in both number and capacity. Some design professionals are describing the ability they provide to generate new architecture as a paradigm shift. The best of these processes allows for innovative new forms that bring architecture back to us through a series of processes that mimic nature’s own evolutionary optimisation systems. However, it is misguided to think that these programmes can be loaded up, set loose and adequately, let alone optimally, resolve complex design problems without intervention by the architect at critical stages of the design process. Failure to intervene, adapt, or simply understand an algorithm’s form-giving qualities entirely is to blame for the unfortunate series of mystical optimisation and analysis systems computational architecture has spawned thus far. One thing that is clear is the definite convergence occurring between architecture and engineering disciplines, facilitated fundamentally by the interchange of data via parametric modelling software. The aim of this research is to establish creative methodologies that celebrate the necessary symbiotic relationship between architect and computer/scientist by way of experimentation. The aesthetic implications of this are certainly unprecedented.
Acknowledgements

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INTRODUCTION

Problem Statement

Two years ago I wrote a research proposal that devised a novel application for the most literal of interpretations of the term ‘alloplastic’ as it is presented by Mark Goulthorpe in describing the potential of the reconfigurable surfaces he first theorised in his 1995 *Prosthesite* project.  

It asked how the reconfigurable alloplastic, Aegis Hyposurface could alter or ‘optimise’ its form so that wind movement across a site could best be directed towards building-integrated wind turbines. This would have been, to the best of my knowledge, the first research into responsive topology optimisation. I still feel this is an area worth perusing further; however, it was not until I actually began this pursuit that I discovered that pre-physical forms of the alloplastic, (that is, those still subject to the indeterminate generative processes within the computer itself), posed more pertinent questions.

As early ago as the 1997 Virtual House competition, Akira Asada was the first to document what at first glance may seem like a trivial point. His point, and its relationship to the notion of the alloplastic, is that of the ‘stopping problem’, a fundamental consideration in any computer modelling process. Why stop transformations at a particular stage? What is the rationale behind the selected digital form, frozen as it were, *becoming* the design iteration deemed best by the designer, selected in preparation for its physical realisation as a static representation of the alloplastic digital form finding process? Most problematic for computational architecture is that many of its practitioners fail to display a sound rationale when their work is met with these questions; the iteration they choose to stop at and materialise as architecture is often given pseudoscientific misappropriation as justification for selection.

This thesis argues that in order to avoid an inane or deterministic digital materialism engulfing architecture, subjective intervention by the architect at critical stages of the algorithmic form-finding process is needed. The major contribution made here is the philosophical argument culminating in the creation of a framework enabling the theoretical positioning of a practitioner. A series of experiments is used to document the points at which I intervene and the processes

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2 In the jury discussion of the “Virtual House”. In: ‘Any’, no.19/20, 1997, P.33.
that define those interventions. A case study has been selected that I feel is most suited to gestate these results. It is in the creation of these new methodologies that the other chief contribution is made. Combined, these contributions are used to help determine:

the aesthetics of topology optimisation and non-standard analysis

**Research Question**

The aim of this research is to discover and document valid creative points of intervention an architect can take in the design process of computational architecture so as to avoid either an inane or deterministic outcome. What is the methodology behind these interventions and how does it create a symbiosis between architect and algorithm?

**Research Method**

A literary review of the current state of knowledge in the area of computational architecture forms the secondary research and argument. The primary research is undertaken through experimental design studies used to collect data on points of intervention and document the creative processes that define those interventions. Three different topology optimisation algorithms have been selected, and subsequent methodologies for intervention developed for application to a case study at Auckland Airport. Specifically, the processes are being applied to the design of an air-traffic control tower, which also serves as the roof structure of the Intermodal Transport Centre. The location of these new elements corresponds to their intended location as defined in the Auckland International Airport master plan document 2005 to 2025.³

³ *Auckland Airport: the next 20 years and beyond, Masterplan: 2005 to 2025*. Also available at http://img.scoop.co.nz/media/pdfs/0603/AIAL_Masterplan_FINAL_ISSUE_BRIEF.pdf
This thesis forms a comprehensive review of the current state of computational architecture, however, because of the relatively short duration of this research; the experimentation work focuses on topology optimisation and non-standard analysis tools. It is understood that the implications of digital determinism and my proposed methodology defining necessary points of intervention by the architect at stages throughout the algorithmic design process in order to avoid this, apply to the wider field of computational architecture on the whole.
Ten years ago, in the seminal interview with Praxis: ‘Precise Indeterminacy’, Mark Goulthorpe talked about the emergence of the non-standard and the architectural notion of alloplastic and its etymological relationship to the definition first ascribed by psychoanalyst Sandor Frenczi. He also left us with this warning regarding the new technologies at hand:

“There is the danger of an inane digital materialism if it is pursued as technique, if the tenets of new software and machine processes are taken as a new Bauhaus logic.”

Despite the inherent variability suggested by computer systems, this worrying trend has started to manifest itself. To understand the reasons why, one only needs to look at the most prevalent case of mass uniformity so far spawned by computational architecture, that of the voronoi diagram. The voronoi algorithm’s popularity is now such that it can be considered in mystical terms as ‘the golden mean of computational architecture’. It seems the main reason behind this popularity – beyond ease of application, the fact that it shares a common denominator with the golden mean, and the very numerous other manifesto stagnating architectural history – is that of the implied association to biology. Although not driven by the obsessions of a single man, there are clear similarities between the voronoi algorithm and that of Le Corbusier’s Modulor. Through the application of their system to a design problem or domain, both proclaim to offer aesthetically beautiful but, also in the case of the voronoi, structurally optimal forms. The commonly implied association through the use of this algorithm is that nature and the inherent

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4 Mark Goulthorpe, *The Possibility of (an) Architecture* (New York: Routledge, 2008), 126. The terms that Goulthorpe successfully adopts to define what he sees as the critical change apparent in architecture come from his translation of the meaning ascribed to them in relation to trauma by Sandor Ferenczi in Laplanche and Pontalis *Vocabulaire de la psychoanalyse*. Paris: Presses Universitaires de France, 1973, p45: “Autoplastic – Alloplastic: Terms qualifying two different types of reaction or adaption, the first consisting of modification of the organism alone, the second a modification of the surrounding environment.”


structurally optimal, aesthetically beautiful solutions it gives will automatically transfer themselves in the birth of, yet another, voronoi form. 7

**Definition.** The term morphogenesis is derived from a literal translation of the Greek words *morphê*, meaning shape, and *genesis*, meaning creation or origin, literally then, ‘beginning of the shape’. 8 It is the biological process that causes an organism to develop its shape. It is also the meaning ascribed to the title given to the computational architecture movement by Manual De Landa, who proclaims it to be a paradigm shift for architecture. He believes that it will “replace design”9 and allow architects to “breed new forms”. 10 Unfortunately the breeding programme De Landa believes is responsible for architecture’s paradigm shift is generating both scientifically and philosophically deformed results through the misguided whimsical application of generative algorithms to design problems that they are simply unsuited to resolve. The voronoi is the archetypal example of this because of its now well-established prevalence, evident in both browsing the Grasshopper forum and in the numerous built, architectural, examples populating the planet. The argument made against the use of the voronoi ultimately being against the practitioners of computationally generated voronoi patterns who are falsely proclaiming them to somehow naturally as if by association perform structural tasks in an inherently optimal way. I am certainly not the first to be aware or raise concerns of this aspect of the problem; my own FEA testing on a voronoi design domain mimics the results of those done by Dimitrie Stefanescu who notes “If you do a simple FEA analysis on a voronoi cell grid, you will see you’ll probably need more steel than a simple orthogonal grid to support the same loads, you will double production and building costs, besides getting less flexibility in terms of interior organization.”11

The reason behind the lack of transference between what, at a cellular naturally occurring level, is an optimal structure and versions generated digitally to perform at an architectural scale is simply that; one of scale. There is a huge difference in scale between naturally occurring

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7 The prevalence I refer to is most evident in browsing the Grasshopper 3D forum, having become the central online community for the discussion of generative algorithms. Many projects are found to be rendered in the light of performance yet offer little substance to this implied science, the voronoi becoming the archetype.


10 Ibid.

cellular voronoi, found under microscope at roughly $1 \times 10^{-5}$ m, and the architectural structures people are generating, starting at around $10^1$ m. The reason the voronoi performs so well in its naturally occurring cellular state is due as much to its materiality as to the pattern itself. So, for voronoi to accurately transfer their performative qualities to an architectural scale, naturally, we would have to build in the same way nature does, using far smaller building blocks than the simple ones we currently employ. For this reason, the next generation of digital fabrication and analysis techniques have the potential to render the current argument against the use of the voronoi at an architectural scale invalid due their ability to more closely mimic nature’s building processes. This exciting scenario is bought about by the development of Variable Property Analysis (VPA) and Variable Property Fabrication (VPF) techniques pioneered at the Massachusetts Institute of Technology. Applications for and implications of this advanced fabrication method are the current research work of Nervi Oxman. The science is based on the concept of Functionally Graded Materials (FGM), which are “characterised by the gradual variation in composition and structure over volume.” The most profound implication of this development is the impending reversal of our well-established design sequence. Architects traditionally set about by designing form and giving it structure. They ultimately arrive at assigning materiality as a result of the first two processes. Here, the sequence is entirely reversed in that we begin by designing the functionally graded material to fulfil the structural task imposed by the brief’s pragmatic requirements, and end up ‘finding’ the form, shape or lineamenta of the architecture on the basis of these first two stages. While these are fascinating fields, the advances they promise only magnify the importance of this thesis in that the fear exists of an environment of magnified irrationality induced in their adoption by those who have evidently failed to grasp the most basic of digital morphogenetic concepts. You don’t give a child Lego until he first masters the use of Duplo.

14 Although somewhat of an obvious conclusion, ideas forming this argument were first extrapolated from: Nervi Oxman, “Structuring Materiality: Design Fabrication of Heterogeneous Materials,” Architectural Design 80, no.4 (2010), 78.
15 Alberti’s concept of lineamenta highlights the fact that by designing and constructing through such a method, one that more closely mimics nature’s processes, the discussion of res aedificatoria would have been possible as a science in Aristotelian terms: given that a building constructed in this natural way could have been considered to have an essence.
The fundamental issue that must be resolved in order to progress computational architecture’s paradigm is one of intellectual integrity, finding its origins in the ability a person has, or lacks, to be self-critical. The importance of stopping the problem at the source through efforts made by educators must be emphasized in order to avoid the looming magnification of the initial pseudo-science that has come to define much of computational architectures output. For this reason, the voronoi, with its associated luggage, becomes the prime candidate for an introductory learning tool. Teaching a class on computational architecture and setting a task that calls for 2D and 3D applications of the voronoi diagram should come first. As a study, it would highlight a student’s ability to think creatively but also clearly establish those students who are able to think critically. Expanding on the pedagogical significance, it is here one could make detailed comparisons between the voronoi and the ‘Nine Square Grid’ project; that fantastic diagrammatic study given to many students of architecture. A full analysis of the similarities is beyond the scope of this paper; suffice to say that in giving students a voronoi project the ease of differentiating between those who truly understand computational architecture and those who just wanted to make pretty shapes would be clear. The voronoi diagram’s value, beyond an initial introduction and experimentation tool, must be understood for what it isn’t in order to progress further along the path of computational architecture, in doing so, also learning from modernism and architectural history’s greatest error; the narcissistic creation of manifestos that attempt to define a universal ideal. Current iterations of voronoi output, despite what popular architectural culture may be selling, are certainly not ideal.

The problem has a wider scope, which is illustrated by the Novotel Hotel, Auckland Airport, 2010. Computer-generated renders of the 12-storey hotel present a building that appears to offer a uniform ‘diagrid’ structural solution. A common yet valid reason for the use of the diagrid structural solution is the reduction of total steel usage it affords, in some cases around twenty per cent. Applied use of a diagrid system therefore offers an innate form of structural optimisation to an architectural problem; however, the Novotel building only pretends to offer all the performative advantages of a coherent diagrid construction. By applying something of a

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16 This building was under construction at the time I selected my case study site. My initial thoughts based on the drawings presented to me were that it shared similar intent to the design goals I sought to generate through the application of topology optimisation algorithms to the control tower. For this reason I thought the two buildings would create a harmonious relationship. The built reality could not be more contradictory.

17 Barry Charnish and Terry McDonnel, “The Bow: Unique Diagrid Structural System for a Sustainable Tall Building” (Paper presented at the CTBUH 8th World Congress, 2008)
diagrid veneer to the southern and northern façades of the building, the architects of the Novotel are masking the more conventional and less performance-oriented construction of the traditional moment frame hidden beneath. Given the inherent savings a diagrid system brings, one can only assume the architects want the building to look like something it is not, in that this veneer is intended to be read as ornamentation, designed in the great postmodern tradition, simply to *evoke* by way of imagery the ‘real’ diagrid system architecture’s successor apparent, digital morphogenesis, would go about constructing literally.

Manual De Landa, not alone in his painting of digital morphogenesis as architecture’s new paradigm, is joined in the cause by another prominent theorist Neil Leach. Leach takes on the more prominent role of promoter of the apparent shift in his publication *Digital Morphogenesis* and book *The Anaesthetics of Architecture*.¹⁸ ¹⁹ Leach makes no apologies for his declarations, making clear in the opening lines: “This is a polemical work. In an age when manifestos and polemics have become somewhat unfashionable, such a work may appear out of place.”²⁰ If the drawing of parallels between Leach and Le Corbusier, the voronoi and the golden section were not already clear, then they should be now. The proselytizer approach taken by Leach is one that succeeded for Le Corbusier; both *The Anaesthetics of Architecture* and *Towards a New Architecture* work to build a rapport with fellow architects through the basic premise that the prevailing paradigm is inadequate and ought to be replaced by mass adoption of the new.²¹ Where it can be said that Le Corbusier succeeded, Leach’s attempt is debatable. This phenomenon of attempting to define the details of the shift apparent is not limited to proclamations expressed via manifesto:

“What characterizes most architectural conferences is that everybody is saying we’re in a new environment, that there’s a paradigm shift of some sort, but everybody seems to flounder at giving examples of and articulating what it is that’s new.”²²

For this reason before even considering listing the qualities of the shift apparent, whether self-imposed or otherwise, it is appropriate to look at what constitutes a shift, so that an assessment of the current environment can be made against it. The definition of a paradigm shift is such that a

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dramatic change in methodology or practice within a field must take place, but additionally requires almost universal adoption amongst practitioners of that field to be considered so. A paradigm shift is nothing short of a revolution; one that is simply unapparent in the proclaimed shift from postmodernism to digital morphogenesis. If, for argument’s sake, a paradigm shift was taking place, it would be interesting to hear what De Landa and Leach make of buildings such as the Novotel and algorithms such as the voronoi being marketed to developers by architects under the guise of digital morphogenesis, when in reality the theory behind the aforementioned solutions amounts to nothing more than a pseudo-sustainability rant. Surely they too would see the paradox here, being a contradicting mix of postmodernist references by way of performance evoking imagery, ornament and veneer in order to mimic the potential of (an) architecture, the potential of a valid optimal. Digital morphogenesis here is reduced to nothing more than the blatant mysticism similarly professed in the infamous manifesto Le Modulor over half a century earlier.

It seems we have learnt nothing from architectural history. Ultimately in the example of the Novotel’s veneered diagrid, lies the biggest irony to Leach’s claim of a paradigm shift from postmodernism to digital morphogenesis. For it is only in the preface of The Anaesthetics of Architecture where he describes postmodern architecture as “design reduced to the superficial play of empty, seductive forms and philosophy appropriated as an intellectual veneer to justify forms.”

The problem fundamentally lies in the intellectual integrity of architects. Evidently the ease of applying pseudoscientific algorithms or simply a desire to mimic the ‘look’ of the optimal is behind the widespread lack of adoption of valid systems of topology optimisation that should be coming to define the aesthetic of the actual paradigm shift only just beginning to take place. There are a few possible reasons behind the lackadaisical approach. The first is pragmatic in that many of the valid topology optimisation techniques mentioned are still beyond the reach of most architects due to the “complexity of mathematics involved” and the often obscure and cumbersome software used in generating a solution. The second and more worrying, for it can’t be learnt, or rather unlearnt, is a problem that finds its origins in the twisted philosophical

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position adopted by many of these architects. One way to answer how such a stance could be considered acceptable is through an analysis of the thinking of one of the main protagonist’s writing. De Landa’s work focuses on the theories of the French philosopher Gilles Deleuze on the one hand, and modern science on the other.\(^\text{27}\) This fact in itself should automatically raise interest as to where his true beliefs lie, for Deleuze’s theories originate from the school of continental philosophers, who generally reject scientism; thinking that does not bode well in its application to a movement that is fundamentally based on computer science and biology.\(^\text{28}\) In this conflicting light, it is possible to understand how De Landa and architects whose critical thinking originates from the era of postmodernity, such as those who designed the Novotel, are stuck practicing a brand of architecture that, although wanting to be optimal on the one hand, is just as happy to pretend or signify an optimal on the other.

Issues regarding the aesthetics of topology optimisation have seldom been raised before. There is little or no discourse on the topic. This is likely due to the lack of architects trained to utilise topology optimisation in the design process, being traditionally the domain of the structural engineer. One of the few insights available comes from an interview by Terri Peters with Ole Sigmund, Professor at the Department of Mechanical Engineering, Section for Solid Mechanics, Technical University of Denmark. When asked by Peters how something should ‘look’ optimised or perhaps look ‘not’ optimised, Sigmund gave this insightful answer:

“I certainly think that an optimized structure is beautiful. However, due to my training I see many flaws in “optimized structures” that ordinary people would not see. Hence, a structure with many circular holes may look light and efficient for many people, however, in my eyes I see stress concentrations and waste of material. Also if I see a curved bar that is supposed to support longitudinal forces I know that the structure is not optimal… A good example of this faulty optimization is the CCTV tower in China. The outer structure is claimed to distribute the forces in an optimal way, however, to me it is


clear that it is by no means optimal and that a much better (and possibly even better looking) (outcome) could have been obtained using topology optimization.”

The ‘flaws’ Sigmund refers to are both evidence of a pseudoscientific digital morphogenetic condition prevailing over valid algorithmic methodologies, and of the paradoxical philosophical stance taken by architects, comfortable allowing such ‘faulty’ forms of optimisation, good enough, as it were, for signification purposes. Sigmund raises another complicated argument that is as long as architectural history itself and perhaps about to get a little longer. His statement “I certainly think that an optimized structure is beautiful” could not be considered a purely aesthetic judgement from a formalist position. The formalist position would be to dismiss such a statement on the grounds that it is a conceptual judgement of beauty. Sigmund thinks that an optimised structure is beautiful. His statement relies on the idea of an optimised structure in the judgement of its beauty, instead of his appreciation being solely in the “disinterested desire for beauty”. As aesthetics deals with not only the nature of beauty but also the creation of that beauty, it is possible to argue that a formalist position may still be maintained by a statement such as Sigmund’s if you view the ‘idea’ he refers to, being the consideration of the ‘beautiful structure’ under the presumption that structure is now a natural process, rather than a man-made one. We are now in an environment, brought about in part by the VPA and VPF processes, which has had the effect of reshuffling materiality into its rightful and logical position, at the forefront of design. We now start by designing a material. The design of materials that mimic nature’s processes and the application of them to structures through topology optimisation being a set of processes containing no rules with fixed ratios different to any of those already imposed on everything within our environment under the very natural laws of physics. Adolf Hildebrand states in his Problem of Form, 1893, that proportions must be formulated for every new composition of elements, they must be discovered for each individual object. I similarly argue the importance of a design methodology that ensures true discovery of form, achieved through a symbiosis between architect and algorithm in order to avoid a deterministic outcome. The issue

30 Ibid.
32 VPA – Variable Property Analysis, VPF – Variable Property Fabrication.
is decisively resolved by the realisation that an optimised structure is no longer simply a concept or idea. It transgresses the boundaries of idea by no longer being representational, in that it has to some degree actually become nature itself.

It is in the aptly titled thesis “Evolving Digital Morphogenesis” that Daniel Davis makes similar arguments. Davis believes current manifestations of digital morphogenesis to be lackluster, focusing his critique on Neil Leach by exposing the fallacies Leach falsely attributes to digital morphogenesis.\textsuperscript{34} Leach, for example, claims, “The ‘designer’ merely establishes certain defining coordinates, and then unleashes the program.”\textsuperscript{35} Davis rebukes this, “Because digital morphogenesis cannot be ‘unleashed’ on all problems, at the very least the architect is responsible for designing what digital morphogenesis cannot.”\textsuperscript{36} Architecture in its entirety is a complex beast, and the reality is that any paradigm we find ourselves in, output and generation of (an) architecture will always be done so under human control. Digital morphogenesis is only suited to resolving particular problems within architecture, the narrow range of effective applications for the algorithmic capabilities of a computer I believe most promising becoming the experimentation tools used to help answer this thesis. The important point to note here is that both Davis and myself are researching the implementation of tools and processes that seek to allow architects to retain control over the design process, ensuring a symbiosis between architect and algorithm is present in order to avoid the ‘inane’ and deterministic models Goulthorpe warned of so many years earlier. The method Davis advocates to achieve this symbiosis is through his pioneering application of Patero-optimisation.\textsuperscript{37} The method allows the architect to tailor the form-finding process so that fitness, the term used to define the qualities of a particular iteration, can be given multiple objectives. This facilitates a collaborative approach between the architect and computer in that the architect makes subjective decisions as to what qualities define the multiple objective search field, while the computer is employed to perform the complex calculations the architect would otherwise struggle to resolve. I sense the Patero-optimisation approach has much potential but warn of a possible watering down of the tectonic optimal

\textsuperscript{34} Davis D, “Evolving Digital Morphogenesis by means of Biology and Computer Science” (Master’s thesis, Victoria University, Wellington, 2009), 8.
\textsuperscript{37} Davis D, “Evolving Digital Morphogenesis by means of Biology and Computer Science” (Master’s thesis, Victoria University, Wellington, 2009), 47.
solution when too many objectives make up the fitness selection criteria. I disagree with Davis on the degree of success to be had in implementing any current computational analysis technique in the resolution of spatial planning issues.\textsuperscript{38} This domain of architecture is best left entirely to the architect’s innate abilities. All of the topology algorithms implemented in my structural form-finding exercises below take their initial form-giving parameters from the pragmatic requirements extracted from the brief and are therefore innately multi-objective. The hierarchy of what I determine to be the importance of the movement of people around the building and site taking precedence, the topology algorithm applied then based on points of support that are known not to hinder this movement. The fact remains that our methodologies, although different, are put in place to ensure the architect retains control over the design.

The application of computational methods to the analysis of spatial planning configurations is a concept originally conceived of by Bill Hillier and colleagues at University College London during the early 1980s. The group called the theories and techniques ‘Space Syntax’.\textsuperscript{39} The subsequent work of Pritesh Patel highlights the limitations of space syntax through an analysis of airport terminal floor plans using the Depthmap space syntax engine.\textsuperscript{40} Although there is obvious confusion on the subject as early on as the definitions section of his thesis, meaning nothing much can be expected to be gained by reading further, it is interesting to look at his inflated perception of the capabilities of space syntax, found in the conclusions he draws from his research of the software. Patel uses his research findings to devise a manifesto he entitles “The 7 Design Rules”.\textsuperscript{41} The ineffectiveness of creating rules that seek to improve space value is an argument already effectively expressed by Geoffrey Scott and many other formalists whose lineage dates back to Kant and his insistence that “A judgement upon an object of our delight must be wholly disinterested”.\textsuperscript{42} A formalist position is only aggravated further with the creation of rules that are based on an antiquated tool, one having already seen heavy criticism for its flaws amongst academics, the most noteworthy coming from Carlo Ratti and his technical description of the inconsistencies.\textsuperscript{43}

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\textsuperscript{39} Bill Hillier, \textit{Space is the machine} (University of Cambridge: Press Syndicate, 1999), preface.

\textsuperscript{40} Patel P, “Digital Exploration & the Airport Terminal” (Master’s thesis, UNITEC, 2009)

\textsuperscript{41} Patel P, “Digital Exploration & the Airport Terminal” (Master’s thesis, UNITEC, 2009), 44.


to illustrate the major weakness of the spatial syntax engine. In stating the rule “Create a clear sense of direction by way of the architecture”, intended to be resolved through the application of space syntax analysis to his own floor plan, he creates a rule for the resolution of an architectural problem he believes will be more adequately resolved by space syntax analysis rather than his own planning abilities.⁴⁴ A tragic fallacy; only magnified in the sense that it is the very authorities on the topic, De Landa and Leach, who through their polemical writing advocating the removal of the architect from the process and the “unleashing” of the computer program, become the leading protagonists of such a position.⁴⁵

A technical description forming my complete argument against the Depthmap spatial syntax software is beyond the scope of this paper, however, it has to be said that, in direct relation to Patel’s ‘rule’; the application of analysis software that fundamentally works only via analysis of a 2D plan must surely be seen as inadequate in its application to spatial planning, which involves consideration of our very three-dimensional world. This brings attention to an example of ‘inane’ software, driven by inane thinking that can only result in the inane digital materialism warned of by Goulthorpe.⁴⁶ However advances have been made through the promising work of Daniel Hambleton and his team who are developing Dragonfly, an artificial intelligence (AI) engine that attempts to link the theory of ecological perception to architecture.⁴⁷ As described similarly in the case of the voronoi, next-generation advances made in the field have the potential to give validity to the use of a space syntax engine such as Dragonfly, at least via a combinatorial approach maintaining the subjectivity of the architect’s input, which as this thesis proposes, must always be present to avoid a deterministic model.

I highlight finally the convergence of the once individual disciplines of structural engineering, computer science and architecture bought about through the direct exchange and application of data enabled by parametric modelling software; as being the most evident aspect of the paradigm shift proper in emergence. “Topology optimisation offers considerable potential within architectural design as a driver of design innovation and the convergence of the

architectural and engineering disciplines.”  

The beginnings of this shift, which it can be said were bought about by the transition to digital technology itself, have now matured to the degree that it is causing “a massive upheaval in our base patterns of thought” and fostering an “emergent mode of creativity” that is not discipline specific, as Dr. Don Ingber of the Wyss Institute describes in his lecture Biologically Inspired Engineering:

“All the boundaries between the disciplines in the sciences, biology, physics, chemistry computer science and material science are all breaking down. As a result we are really learning fundamentally how it is that nature builds from the bottom up. As a result of this convergence the boundaries between living and non-living systems are beginning to break down.”

Certainly it is true then that we will be aware of a definitive paradigm shift within architecture when signification to nature of any kind returns to the casual artistic pursuits of the canvas, our buildings themselves becoming nature, no longer a representation of any kind of idea.

**Conclusion**

This review uncovered the need for higher levels of intellectual integrity amongst the practitioners of computational architecture. This need will only become more important as we take on the next generation of design analysis and fabrication techniques, which will come to solidify the shift proper, ultimately seeing an end to signification or representation within architecture as we return ourselves to nature. The issue of intellectual integrity will always be at the forefront in ensuring a voice is given to that which deserves just recognition and equally that which does not. Although in a constant evolution it is at times like these, when the makings of a definitive shift are upon us, that this voice is most important, there to ensure an accurate heading is maintained.

In order to avoid a magnification of the pseudoscientific traits exposed in this review as technological advances push the paradigm shift proper into reality, I have devised a scale of

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48 Per Dombernowsky and Asbjon Søndergaard, “Three-dimensional topology optimisation in architectural and structural design of concrete structures” (Paper presented at the IASS symposium, 2009)
theoretical positions. These are presented in the methodological approach section of this document with the intention of creating a framework for the assessment of practitioners. By presenting my discoveries from the experiments devised, I am giving examples of the “emergent mode of creativity” Mark Goulthorpe describes as being brought about by the paradigm shift proper, one I hope will gain definition through work created under an abnumeral-optimal methodology.  

METHODOLOGICAL APPROACH OF THE PROJECT

Theoretical Positioning

The review of the current state of computational architecture shows a severe lack of intellectual integrity by architects is to blame for fulfilling the prophecy of Mark Goulthorpe. Both the inane and deterministic are characteristics that have become prevalent in our built environment because of both a lack of intervention by the architect within the algorithmic design process and the inappropriate application of algorithms resulting in the pseudoscientific. The irony of this is huge when considering the argument made by De Landa et al. that a paradigm shift is taking place within architecture. For, within the same manifestos that have come to be defined as prominent discourse on the topic, much of the argument they make for this shift is couched in terminology that seeks to remove the architect, seemingly entirely, from the design process. Because of this, and in order to help devise a solution to the problem, I propose a scale that, when applied in assessment of a computationally generated work, enables a theoretical positioning of the practitioner. This scale affords three positions, making reference to the other aesthetic framework all architects can place themselves within: formalism, anti-formalism or moderate-formalism.

They are Anti-Optimal, Formal-Optimal and Abnumeral-Optimal

Position One: Anti-Optimal

The severe end of the scale is the anti-optimal position. A work deemed so presents with characteristics that are highly pseudoscientific. Architectural production generated using inane methods such as those critiqued in this thesis, including but not limited to the ‘voronoi algorithm’, the ‘Novotel diagrid’ or current ‘space syntax’ applications, are examples worthy of designation within this category. It is impossible for a computational architect employing valid topology optimisation algorithms to be classified as anti-optimal. However, this does not necessarily mean avoidance of formal-optimal classification.

Position Two: Formal-Optimal

A computational practitioner deemed formal-optimal is one who strictly selects only the form generated by the computational algorithmic process, without any intervention outside this
process at any iteration. This position is unfavorable because, by definition, it can only lead to technological determinism, in that a deterministic system is one in which for everything that happens there are conditions such that, given them, nothing else could happen.\textsuperscript{52} This is also a position of ‘tragic fallacy’; in the sense that it is the very authorities on the topic, De Landa and Leach, who, through their polemical writing advocating the removal of the architect from the process and the “unleashing” of the computer program, become the leading protagonists of such a position.\textsuperscript{53}

\begin{center}
\begin{tabular}{ll}
\textbf{Position Three:} & \textbf{Abnumeral-Optimal} \\
0.0.3 & \\
\end{tabular}
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The word abnumeral is first used in a series of lectures given by Charles Sanders Peirce at Cambridge University in 1898. The meaning Peirce ascribes to the word is in reference to a set of numbers that he says are distinct or uncountable; they are “\textit{abnumeral}.”\textsuperscript{54} It is this interest in abnumeral, having the connotations of being uncountable that has lent itself to describe experimentation into the creation of methodologies that, on one hand rely heavily on the pure mathematical domain of the computer, but seek to intervene through an ‘uncountable’ or abnumeral action on the other. Abnumeral-optimal being then the theoretical position afforded to a computational architect who not only employs valid topology algorithms in the computational generation of form but also employs creative processes of intervention by way of non-standard analysis. This ensures avoidance of either an inane or deterministic outcome, and celebrates the symbiotic relationship of computer and architect. Therefore, the experiments contained here are used to help define

\textit{The aesthetics of topology optimisation and non-standard analysis}

TOPOLOGY OPTIMISATION EXPERIMENTS

Abnumeral 1.0:  Lines of Principal Stress

0.1.1  Aim:
To document the relationship fostered between architect and computer through cross-validating results generated from analog and digital structural analysis processes.

0.1.2  Brief:
Design the air traffic control tower and roof structure to the Intermodal Transport Centre using topology optimisation and non-standard analysis methodology.

0.1.3  Site:
The processes are applied in the design of an air traffic control tower that also serves as the roof structure of the Intermodal Transport Centre. The location of these new elements corresponds to their intended location as defined in the Auckland International Airport master plan document 2005 to 2025.55

As previously mentioned all of the topology algorithms implemented in my structural form-finding exercises take their initial form-giving parameters from the pragmatic requirements extracted from the brief and are therefore innately multi-objective. The hierarchy of what I determine to be the importance of the movement of people around the building and site taking precedence, the topology algorithm applied then based on points of support that are known not to hinder this movement. Some of these pragmatic form-defining requirements included:

55 Auckland Airport: the next 20 years and beyond, Masterplan: 2005 to 2025. Also available at http://img.scoop.co.nz/media/pdfs/0603/AIAL_Masterplan_FINAL_ISSUE_BRIEF.pdf
- That the towers control module be of sufficient height to ensure clear line of sight to all gates.
- Researching the likely weight range (gross) of a control tower module this size (12m Dia) to ensure accurate loading figures could be applied.
- That access to the control tower module, public viewing platform, and dining level were considered in loading calculations.
- That the ground floor area of the intermodal transport center was of adequate proportions to contain all necessary facilities and services.
- That the impact of such a large voluminous addition to the environment be understood in terms of how its form may affect the ecology of the site.

Schematic showing intended developments, from “Masterplan: 2005 to 2025” 56

0.1.4 Rationale:

This experiment stems from an interest in the form-finding studies of building engineer Pier Luigi Nervi. Nervi developed a design methodology based on the analysis of principal stress patterns in transparent acrylic models under polarized light as a way to assess feasibility of his designs, due to their complexity and inability to be “calculated by orthodox mathematical analysis”. 57

The work of Jon Mirtschin and his Geometry Gym components for Grasshopper, the graphical algorithm editor integrated in Rhino 3-D, together enable early assessment of digital models by generating lines of principal stress derived from Oasys GSA. 58 Optimisation is achieved in allowing structural members to follow lines of principal stress and curvature, with a reduction in material needed to perform the assigned loads because theoretically no shear stress is induced along these lines.

0.1.5 The architect’s role:

Cross-validate results from those produced using the polarized light method pioneered by Nervi, being the analog, and those generated from Jon Mirtschins geometry gym components, being the digital, to ensure accuracy and advance formal iteration changes based on findings from both processes.

<table>
<thead>
<tr>
<th>Abnumeral</th>
<th>Lines of Principal Stress - Digital Findings</th>
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</table>

1.1.0 Process of generation:

1.1.1: 3-D model ‘basic’ tower geometry conforming to pragmatic requirements.

1.1.2: Determine optimal degree of formal deviation from center in relation to ultimate compressive strength using (Scan&Solve)Von Mises Stress component applied with loading conditions simulating control tower weight and materiality (cast acrylic) simulating those being tested in analog process.


58 Jon Mirtschin, “Geometry Gym.” Data found at: http://geometrygym.blogspot.com
1.1.3: Import principal stress vector field into Grasshopper using Geometry Gym Rhino plugin connected to Oasys GSA analysis.

1.1.4: Compare Oasys GSA analysis results (right) with the principal stress vector field results from the Geometry Gym Rhino plugin overlaid onto secondary (Scan&Solve) Von Mises Stress analysis software (left) to test accuracy. Lines of principal stress and curvature match in this case, validating results.

1.1.5: Repeat process to analyse current form iteration, after design decisions significantly altered its dimensions. (Notice the massive widening of the base diameter of the tower; this occurred when it was decided to incorporate the structure of the control tower and Intermodal Transport Centre roof into one continuous form)
1.1.0 Results:

- 1.1.1 - 1.1.5: The digital process used to generate principal lines of maximum and minimum stress for the design domain appears successful after cross validation tests performed in 1.1.4 validate results of the Geometry Gym plugin.

\[
\text{Factor of safety} = \frac{\text{Ultimate tensile strength}}{\text{Maximum allowable stress}}
\]
1.1.6: Attempt to replicate Factor of Safety on yield strength

- Material: Acrylic, General Purpose Mould
  Restraints: Base
  Loads: 50,000N
  Component: von Mises
  Deflection: 500 times intended loading
  Total Max Deformation: 100mm over entire form (139M) or 0.08%

1.1.0 Conclusion:

- The generation of lines of principal stress for the design domain is only part of the way towards an optimal structural solution. To generate an efficient grid structure every intersection of these lines needs to be considered individually as, “at each location one direction might dominate over the other.” \(^{59}\) Meaning an advanced

\(^{58}\) Jon Mirtschin, e-mail message to author, June 8, 2011.
optimal solution would allocate material only where needed at every point along the lines of principal stress generated from the design domain analysed.

- Aesthetically, the lines generated enabled the design to be taken far beyond simply mimicking the look of a valid optimal. The lines are a true and accurate optimal solution; they are the lines of principal stress where material should be deposited and are only one stage removed from detailed design and fabrication.

- In analog/physical model testing it will be almost impossible without proper equipment to replicate the accuracy of the digital Factor of Safety on yield strength test, (1.1.6: ( D = 1mm /1390 or 0.08%) (σ 50,000N) )

<table>
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<tr>
<th>Abnumeral:</th>
<th>Lines of Principal Stress - Analog Findings</th>
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2.0.0

2.1.0 Process of fabrication:

2.1.1: 3-D model form
2.1.2: 3-D print form
2.1.3: Vacuum-form both sides of the 3-D print, join halves
2.1.4: Test transparent model using Nervi’s methodology

2.1.1 2.1.2
2.1.0 Results:
- Failed due to inability to join vacuum formed halves accurately.

2.1.0 Conclusions:
- Even if joined accurately, the seam created would invalidate results due to concentrations of stress at joins.
- The vacuum form process did not ensure even wall thickness of the model and this would also invalidate results.
- A process that generates a seamless representation of the digital form, in a clear acrylic material is needed.

2.2.0 Process of fabrication:
- 2.2.1: 3-D model four part mould
- 2.2.2: 3-D print mould
- 2.2.3: Acrylic resin casting process
- 2.2.4: Test transparent model using Nervi’s methodology
2.2.0 Results:
- Failed due to inability to release cast acrylic model from mould, model fractured on release.

2.2.0 Conclusions:
- The 3-D print generated by the V-Flash process is unsuited to be used in the casting process because the release agent needed to ensure the acrylic resin does not stick to the sides of the mould during the curing process is evidently incompatible with the V-Flash material. Source 3-D printer that prints in acrylic based material.

2.3.0 Process of fabrication

2.3.1

- 2.3.1: 3-D model form
- 2.3.2: 3-D print form using acrylic based photopolymer
- 2.3.3: Test transparent model using Nervi’s methodology
2.3.0 Results:
- Inconclusive, unusable data. As 2.3.3 shows, no stress concentrations are visible.

2.3.0 Conclusions:
- Innate to the rapid prototyping process is the displacement of material in representation of the 3-D form. For the 3-D printer to do this the digital model must be divided into many hundreds of layers across its vertical (Z) axis.
- The layers of material put in place by the 3-D printer, although somewhat clear, had the effect of masking or clouding the model, making it unsuitable for testing.
- The layers of material put in place by the 3-D printer had a similar invalidating effect as seen in the first fabrication process with potential concentrations of stress at layers.
- “Transparent Detail” the acrylic based photopolymer material sourced from Shapeways has since been removed from the market.

Abnumeral 1.0: Conclusion

This experiment successfully showed a convergence of disciplines through the cross-validation of processes usually confined to structural engineering practices. Despite the convergence evident in this work, there will always be a necessary distinction between the fields in the advanced knowledge each can bring. The marriage between the engineer and architect is made more harmonious by the ability the architect now has to predict optimal solutions early on in the design process. There is significant room for further experimentation by the architect following the generation of lines of principal stress that can directly affect the aesthetics of the architecture such as altering the frequency or spacing of these lines in relation to the intended member thickness.
NON-STANDARD ANALYSIS EXPERIMENTS

Abnumeral: Total Direct Radiation (solar gain) 0.0.0

0.1.1 Aim:
To test how changes made to formal elements within the design domain affect Total Direct Radiation (TDR). To show how formal changes affect performance (Wh/m2).

0.1.2 Rationale:
The direct exchange of data made possible by Grasshopper and Geco components enables Rhino CAD geometry and Ecotect analysis to integrate seamlessly. What this means is that it is possible to easily calculate surface performance values in terms of TDR measured in Wh/m2. Geometry can be assessed for suitable placement of surface mounted photovoltaic panels early on in the design process or integrated with existing elements in positions that achieve best possible scenario returns on such an investment. This monitoring of the environment and the use of the data generated to enhance the sustainability of our buildings takes itself to another level when coupled with the reactive, reconfigurable, *alloplastic* architectural components as it then gives us the ability to alter geometry in real time so that targeted levels can be reached.

The weather data file (.wea) applied to the project site at Auckland Airport was sourced from the New Zealand National Institute of Water & Atmospheric Research Ltd (NIWA) The test area being the existing international terminal main concourse area. (below)
1.1.0 Process of analysis:

1.1.1: 3-D model existing geometry and test
1.1.2: Reconfigure geometry and retest
1.1.3: Reconfigure geometry and retest
1.1.4: Reconfigure and test considering pragmatic requirements
1.1.0 Results:

- Successfully shows alteration of geometry is able to achieve desired surface specific performance values in terms of TDR measured in Wh/m².
- Form is found as a result of the relationship between desired TDR and space function.

1.1.0 Conclusions:

- The potential of maximum returns requires reconfigurable surfaces.
- A commercially viable process accessible to all levels of architectural practice.
- Valid example of: *the aesthetics of topology optimisation and non-standard analysis*

1.1.5 Analysis of tower shows the surface areas that would receive the most hours of TDR, cumulative over the course of a year measured in Wh/m². Yellow indicates the most hours (northern facing façade).
0.2.1 Aim:

To assess the implications the towers form has on its environment in terms of air movement and distribution.

0.2.2 Rationale:

This experiment also takes advantage of the newfound possibilities bought about by the direct exchange of Rhino CAD geometry using Grasshopper and Geco components, but in this instance ‘talking’ to WinAir4.0 a CFD air flow analysis program. What this exchange enables is the ability to alter formal properties of an architecture and instantly reassess implications in terms of air movement and distribution within a design domain. It should be noted that ‘instantly’ is a slight overstatement, in that CFD analysis being the processor hungry process that it is, can take hours, even days to generate a solution.

I felt this experiment especially important and relevant to this site as being such a large, voluminous addition to an environment containing aircraft, many of them lightweight and susceptible to wind gusts, an analysis of the potential air disturbances this element may make is not only important but perhaps design changing.

Inspired by the cross validation methodology pioneered in the Abnumeral: Lines of Principal Stress experiment it would be rewarding to compare this digital analysis to an analog test performed on a physical model in a wind tunnel.
Abnumeral:  CFD - Findings  2.0.0

2.1.0 Process of analysis:

2.1.1: 3-D model existing and new tower geometry and test, review results across X, Y axis (horizontal)

2.1.2: Review across Z axis (vertical) (Wind direction – Easterly.50m/s)

2.1.3: Change wind direction and repeat review (horizontal) (Wind direction – Northerly.50m/s)

2.1.4: Review across X, Y axis (horizontal) at viewing platform height (+96m) (Wind direction – Northerly.50m/s)
Results:

- Tests show the voluminous addition of the tower to the environment at the airport site would cause a significant change in air movement distribution potentially resulting in the disturbance of operations.

- 2.1.2: Wind speed picks up velocity as it passes over the curved Southern façade of the tower and over the top of the Novotel hotel where a large area (yellow delineation) gives readings of up to double the .5m/s test velocity.

- 2.1.3: There are also significant implications, not necessarily negative, at ground level. The Northerly wind induced in this test (.5m/s) shows the area to the southern façade of the tower, being the current entrance to the international terminal, has a notable reduction in wind velocity, readings of 0.02-0.12m/s (blue delineation).

- 2.1.4: This test was conducted to ascertain what kind of wind conditions could be expected on the public viewing platform and hopefully derive the necessary information that would lead to the specific design of barriers and placement of services.

Conclusions:

- The accuracy of the tests is limited by the maximum number of cells possible to be applied to the design domain. Essentially this lack of resolution means that tests such as those conducted in 2.1.4 generate inconclusive results. There simply isn’t enough data to make design decisions at the detail level with this software.

- As results show a potential for the tower to cause a disturbance in operations at the airport, consultation with aerospace engineers regarding the design is advised.

- This experiment could be expanded upon by incorporating the cross validation of the digital and analog methodologies pioneered in Abnumerat1.0: Lines of Principal Stress.

- A commercially viable process accessible to all levels of architectural practice.
0.3.1 Aim:

To determine the effect the towers form has on its environment in terms of shadows cast.

0.3.1 Rationale:

This experiment also takes advantage of the newfound possibilities bought about by the direct exchange of Rhino CAD geometry using Grasshopper and Geco components, but in this instance data is analyzed in Autodesk Ecotect Analysis. The most simple of all the experiments, the CAD model was tested using the same weather data file (.wea) applied to the project site at Auckland Airport, sourced from the New Zealand National Institute of Water & Atmospheric Research Ltd (NIWA) as it was in the Total Direct Radiation experiment.

Tests were conducted on the 25th Day of every month for the year of 2010. Progressive shadow delineation represents a change in time of thirty minutes over the course of the hours of daylight.

3.1.0 Process of analysis:

3.1.1: 3-D model existing and new tower geometry and test, review results
3.1.2: Change month, retest, review
3.1.3: Change month, retest, review

3.1.1
3.1.2 Results:

- 3.1.1: June 25\textsuperscript{th} 2010: taken a few days after the Winter Solstice when the sun is at its most northerly point in the sky.

- 3.1.2: October 25\textsuperscript{th} 2010

- 3.1.1: December 25\textsuperscript{th} 2010: taken a few days after the Summer Solstice when the sun reaches its highest position in the sky.
3.1.0 Conclusions:

- These tests were especially important for planning purposes. Knowing the effect that such a large voluminous addition would have on the site means it is possible to accurately plan the space allocation of surrounding buildings by defining space values. For example, during the winter months when the sun is at its lowest altitude, as it is shown in 3.1.1, the negative effect on retail spaces to the South of the tower is clear. Conversely spaces to the North can be considered to have greater space value; they receive more hours of direct sunlight, and can be marketed on the basis of this data.

- The accuracy of this test is only as accurate as the data collected by NIWA. There are other weather data files available, the most common being the International Weather for Energy Calculations (IWEC) format. In a commercial situation on a project of this scale, cross validating the results achieved from both formats would be necessary to ensure accuracy.
CONCLUSION

This research has shown that it is critical subjective intervention is made by the architect in the computational design process so we avoid a technological determinism engulfing architecture. Too many projects are being produced under a Formal-Optimal ideology, displaying characteristics of this technological determinism, ironic in that such a position is strongly advocated for by ‘authorities’ on the topic.

Perhaps worse is the architecture being produced through pseudoscientific processes. The generation of work produced under this Anti-Optimal ideology has far reaching implications both philosophically and aesthetically. The most negative aspect of this position is that it shows a lack of intellectual integrity by design professionals who knowingly sell the image of computational architecture by rendering, in some cases literally, what is only a veneer of performance, happy to simply signify an optimal.

By way of concluding in this chapter a critical appraisal is conducted by comparing the computational architecture generated as a result of the form finding experiments to the Abnumeral-Optimal theoretical position in order to determine the overall success of the project. Throughout all of the experiments the most profound form altering intervention possible was as a result of the hierarchy I put in place giving precedence to the movement of people around the building and site based on pragmatic requirements extracted from the brief. As the topology optimisation methods were applied based on points of support known not to hinder this movement, alternating the space allocation where I deemed necessary as the project progressed directly altered the resulting abnumeral-optimal. This was the hardest aspect of the project to document here as I had not deliberately recorded the relationship between pragmatic changes and resulting formal changes, instead focusing on recording the cross-validation methodologies. So although I have successfully avoided any inane or deterministic characteristics that would deem the production anti or formal-optimal the lack documentation within showing what is one of one of the main qualities defining abnumeral-optimal production is a weakness. This weakness, one I feel can be resolved during presentation with the help of detailed plans and models contrasts to the biggest strength of the project which I believe to be the key contributions made in the creation of the framework for assessment of computational practitioners and the development of novel methodologies to ensure symbiosis between architect and computer. The resulting
abnumeral-optimal production demonstrating the emergent mode of creativity needed to help propel the paradigm proper into reality $\Omega$

Beyond the refinement and continued testing needed to see true success in the analog vs. digital cross-validation experiments already conducted; other areas offering further research potential include:

- The field of research based on the study of building integrated reconfigurable surfaces and new methods for the capture of data to drive their reconfiguration to our ever changing environment. This is something I coined ‘responsive topology optimisation’, my initial research proposal seeking to optimise such reconfigurable surfaces so that wind movement across a site could best be directed towards building integrated wind turbines.

- Variable Property Analysis and Variable Property Fabrication. Not only is research into the application of these technologies in the fabrication of new materials important, but also are fundamental questions regarding the effect their use will have on the design process. Will they render the argument made against the structural use of the voronoi obsolete? What are the aesthetic implications of a design process that starts with the design of a materials composition?
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