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Doctoral Thesis in Civil and Architectural Engineering

Evolutionary Materialism: Towards a Theory of Anticipatory Adaptive Assemblages

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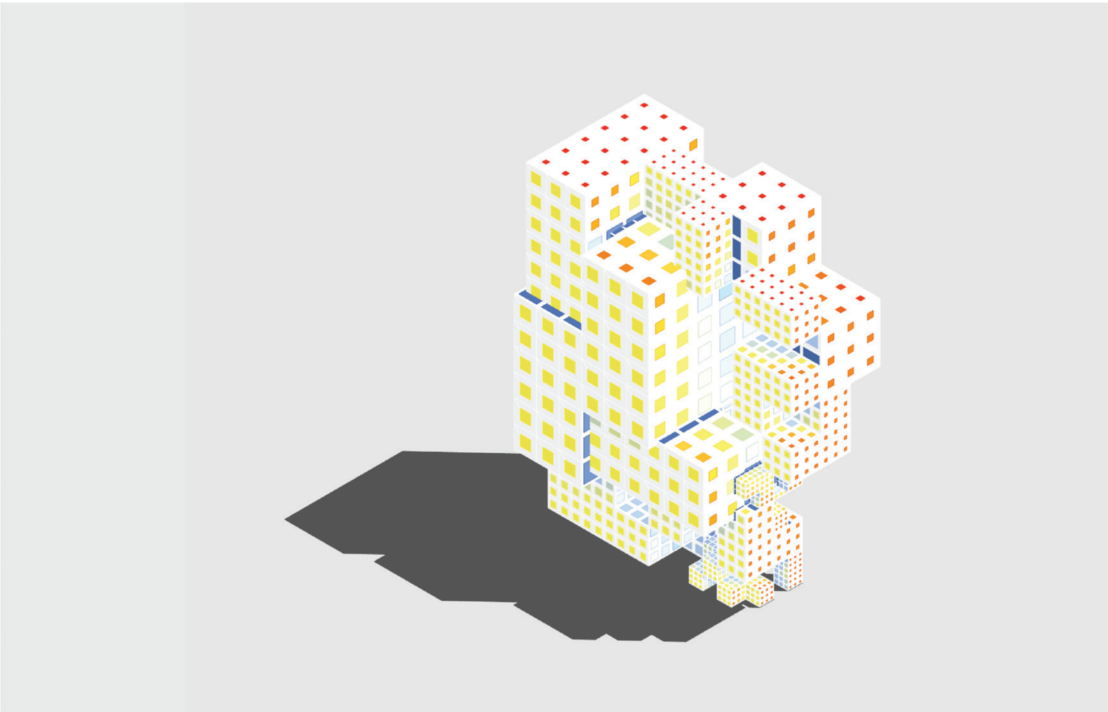

Stockholm, Sweden 2020

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…architects wishing to use this new tool [the genetic algorithm] must not only become hackers (so that they can create the code needed to bring extensive and intensive aspects together) but also be able 'to hack' biology, thermodynamics, mathematics, and other areas of science to tap into the necessary resources. As fascinating as the idea of breeding buildings inside a computer may be, it is clear that mere digital technology without populational, intensive and topological thinking will never be enough.

Manuel DeLanda

…evolution, as opposed to human engineers, doesn't reward designs that are simple and easy to understand.

Max Tegmark

The reason there are no flying dogs isn't that evolution hasn't gotten around to making any yet, it is that the dog lifestyle is supremely incompatible with flying and the sacrifices required to equip a dog with flight would certainly detract more from the overall fitness than flight would add to it. Fitness is the result of a million conflicting forces. Evolutionary Fitness is the ultimate compromise.

David Rutten

…It is a question of surrendering to the wood, then following where it leads by connecting operations to a materiality, instead of imposing a form upon a matter: what one addresses is less a matter submitted to laws than a materiality possessing a nomos. One addresses less a form capable of imposing properties upon a matter than material traits of expression constituting affects.

Gilles Deleuze & Félix Guattari

Embrace the senile genius
Watch him re-invent the wheel

Stephen Malkmus

ABSTRACT

This thesis is an investigation into how meta-heuristic multi-objective optimisation processes (genetic algorithms driven by evolutionary solvers) can bring about materials-related advantages in architectural performance. It redefines the architect's and engineer's role from being designers of a singular space or structure to being designers of entire species of spaces, and discusses a particular method – anticipatory adaptive assemblages (AAA) – that allows such processes to produce many generations of design iterations that eventually yield individuals optimised for a set of predefined objectives. This includes in particular the optimisation of building materials, with a certain focus on timber structures.

The thesis provides a theoretical foundation (assemblage theory) that connects an ontology, a methodology, an epistemology, and an axiology to the computational operations used, elevating the domain beyond simplistic notions of parametricism. It leverages contemporary generative design methods to introduce a range of novel concepts and tools such as auxiliary loads, material phase transition (MPT) diagrams, generative life cycle assessments (GLCA), parametric epistemic things (PET), presilience, and postponism. Finally, it provides a case study that shows how this assortment of contrivances, and AAA theory at large, can be used not just for theoretical musings, but to produce actual architectural schemes based on more precise data analyses than is typically the case in today's built environment.

A concluding discussion establishes that the use of more advanced and complex optimisation strategies is not just a possibility but a necessary obligation for an architecture, engineering, and construction (AEC) industry that – if the manufacturing of building materials are added to the construction and operation of buildings – is responsible for between 35% and 40% of both global final energy use and worldwide energy-related CO_2 emissions. Claiming that our knowledge of materials, including the auxiliary loads that they carry (such as their global warming potential) can be used to design and engineer architectural assemblages capable of replacing energy-consuming with energy-producing buildings, it suggests that Le Corbusier's famous dictum that buildings are 'machines for living in' should be replaced with the notion that all buildings are potential *power plants* for living in. Risks associated with the development of AAAs are discussed, and future studies proposed.

Keywords: *Building materials, multi-objective optimisation, genetic algorithms, evolutionary architecture, material phase transitions, generative LCA, parametric epistemic things, presilience, postponism, anticipation, adaptation, simulation, Grasshopper*

SAMMANFATTNING (IN SWEDISH)

Den här avhandlingen undersöker hur meta-heuristiska flermålsoptimeringar (genetiska algoritmer drivna av evolutionära lösningsmotorer) kan ge materialbaserade fördelar med avseende på arkitektonisk prestanda. Den omdefinierar arkitektens och ingenjörens uppgift från gestaltningen av enskilda rumsligheter eller strukturer till formgivningen av hela arter av former, och diskuterar en speciell metod – anteciperande adaptiva arrangemang (AAA) – som tillåter sådana processer att producera många generationer av designförslag vilka i slutänden genererar individer som optimerats för en rad på förhand bestämda målbilder. Särskild vikt läggs vid optimeringen av byggnadsmaterial, med ett visst fokus på trästrukturer.

Avhandlingen framlägger en teoretisk grund (assemblage-teori) som knyter en ontologi, metodologi, epistemologi och axiologi till de datorbaserade operationer som används, vilket vidgar domänen bortom simpel parametricism. Den använder samtida generativa designmetoder för att introducera en samling nya koncept och verktyg som tilläggslaster, materialbaserade fasförändringar (MPT), generativa livscykelanalyser (GLCA), parametriska epistemiska ting (PET), presiliens och postponism. En avslutande fältstudie visar hur sådana mekanismer tillsammans med AAA-teorin som helhet kan användas inte bara som ett teoretiskt verktyg utan även för att producera faktiska arkitekturprojekt baserade på en mer precis analys av data än gestaltningen av vår bebyggda miljö normalt sett använder.

Diskussionen visar att användandet av mer avancerade och komplexa optimeringsstrategier inte bara är en möjlighet utan ett nödvändigt åtagande för en arkitektur-, ingenjörs- och byggindustri som – om produktionen av byggnadsmaterial adderas till konstruktionen och driften av våra byggnader – ansvarar för mellan 35% och 40% av såväl den globala energiåtgången som världens energirelaterade utsläpp av CO_2. En argumentation för att vår kunskap om material, inklusive de tilläggslaster de medför (som exempelvis deras GWP-värden), kan användas konstruktivt för att designa arkitektoniska arrangemang med potential att byta ut energikonsumerande mot energiproducerande byggnader leder till insikten att det berömda Le Corbusier-citatet om att byggnader är “maskiner att bo i” borde ersättas av idén att alla byggnader är potentiella beboeliga *kraftverk.* Risker associerade med utvecklingen av AAA diskuteras, och framtida studier föreslås.

Nyckelord: *Byggnadsmaterial, flermålsoptimering, genetiska algoritmer, evolutionär arkitektur, materialbaserade fasövergångar, generativ LCA, parametriska epistemiska ting, presiliens, postponism, antecipation, adaption, simulering, Grasshopper*

PREFACE

Divide the people of this world into two sets. Members of the first set need no reason to perform a task; they just get on with it. Those belonging to the second set are distributed along a gradient that at the one end includes those who require just a little bit of context to fulfil their duties, and at the other those who will stop at nothing less than a full investigation into the elementary reasons, principles, and mechanisms of anything and everything remotely related to the topic at hand – or, as the 'holistic detective' hero created by the late Douglas Adams puts it in Adams (1987), 'the fundamental interconnectedness of everything' – to approach their explorations, not rarely at the cost of achieving anything at all.

The author of these pages often envies the people belonging to the former camp, while appreciating fully that he is something of a poster boy for the extreme edge of the latter. It thus follows that this thesis could hardly become anything less than a perhaps overly ambitious attempt to anchor its enquiry not just within the traditions of materials science or engineering, but also within the fields of architecture, philosophy, and the history of science. This generalist attitude, comprehensively described in Epstein (2019), is bound to estrange some readers, in particular those anticipating a traditional (and brief) study on particular material properties. Hopefully it will beguile others. It is sincerely hoped that this state of affairs does not get in the way of the thesis itself achieving its intended purpose.

What, then, might this 'intended purpose' be? An indicative list could sum this up in five points, all corresponding to a theoretical-practical 'evolution' of our reasoning about building materials at the building (rather than the molecular) scale:

1) The thesis repositions the roles of the architect and engineer – henceforth collectively referred to by the acronym AD, for 'architectural designers' – as those of being the creators and controllers of evolutionary systems of material 'assemblages' that yield a plethora of design iterations based on predefined objectives and constraints. Furthermore, it grounds such a repositioning in arguments based on architectural readings of the current theories put forward by philosophers belonging to the new materialist/speculative realist tradition espoused by contemporary luminaries such as Manuel DeLanda and Graham Harman.

2) It outlines a possible trajectory for buildings to be more than (as the currently fashionable trend has it) 'net-zero' consumers, but rather net *producers* of energy. Drawing on Le Corbusier (1923), we may talk about a building not so much as a 'machine for living in' as a 'power plant for living in'. This redefinition of architecture's performative potential could be further developed through a range of sustainable strategies that maximise energy production while minimising energy expenditure (for instance those related to the embodied energy inherent within the materials that make up buildings).

3) It traces the creative development of – and describes in some ontological, methodological, epistemological, and axiological detail – a proposed architectural artefact (an anticipatory adaptive assemblage, AAA) and its associated parametric-genetic design system (in the earlier papers denoted as contextual optimisation workspace, COW). AAA and COW are synthesised using components available within the Grasshopper visual programming environment developed by Rutten (2007), and employs artificial intelligence methods such as

genetic algorithms to design architectural structures, with particular attention to material properties and potentials. This includes, for instance, the optimisation of daylight factors, building orientation, floor area, façade materials, weathering-related aspects, energy-harvesting capacity, global warming potential of wall sections, and fenestration schemes.

4) It uses this design system to produce material phase transition (MPT) diagrams that chart the relative relevance of competing building material systems – representations that allow for comparisons between established material assemblies, analogous to traditional phase diagrams, plotting the critical points at which one system outperforms another given a set of predefined criteria.

5) Over and above MPTs, it introduces a collection of novel concepts and frameworks such as auxiliary loads, generative LCA (GLCA), presilience, and postponism. Finally, it provides a case study that shows how this kind of system can be used not just for theoretical musings, but to produce actual architectural schemes based on more precise data analytics than is typically the case in today's AEC industry. Such design processes are inherently computationally expensive yet efficient from an engineering perspective in that they can be constrained to only produce iterations that fall within a predefined accepted limit – that is, iterations belonging to particular areas within a virtual space of possibilities.

The present thesis is thus an investigation into how such meta-heuristic multi-objective optimisation processes (driven by genetic algorithms) can bring about materials-related advantages in architectural performance. It redefines the AD's role from being a designer of (singular) spaces to being a creator of entire *species of spaces,* and discusses methods that allow such processes to produce many generations of design iterations that eventually yield individuals optimised for a set of predefined objectives. Finally, adapting the assemblage theory originally put forward in Deleuze & Guattari (1980) and later updated and expanded in DeLanda (2002b, 2006, 2010, 2016), it provides a rigid theoretical foundation that connects an ontology, a methodology, an epistemology, and an axiology to the computational operations used, elevating the domain beyond simplistic notions of parametricism and delineating a fertile ground for future studies in architectural and engineering research.

Responding *pre factum* to the expected critique that the thesis strays too far from the beaten track of material laboratory studies, too far into the undergrowth of theoretical concerns, its author offers a combined counter objection and rationale through the simple observation that theoretical examinations of the philosophical realm of materials science are heavily underrepresented in the engineering literature. This is reflected in the elementary chapter headings: it is remarkable to note that after at least 3,000 years of advanced design engineering (Addis 2007) and conjecture on architectural constructions, such fundamental aspects as the ontology, epistemology, and axiology of architecture and engineering need to be *fabricated*, rather than simply *referred to* as an existing system of essentially acknowledged ideas.

The thesis attempts to outline the humble-yet-instrumental beginnings of such a fabrication of basic theoretical components, building blocks for future constructs. Some readers are bound to object to its speculative nature. In Churchill (1898), the 24-year-old army officer

Winston Churchill wrote that he passed 'with relief from the tossing sea of Cause and Theory to the firm ground of Result and Fact'. The present text arguably moves in the opposite direction, tossing, as it were, from the results and facts expounded in its appended papers into theories and conjectures of possible underlying causal mechanisms and theoretical future potentials and applications.

The chapters to follow were written by an architect working 'undercover' within the field of materials science, that is, by what Deleuze and Guattari might have called a 'deterritorialised' scientist: one whose disciplinary boundaries are not strictly defined, and who therefore enjoys a certain amount of intellectual and interdisciplinary mobility. To quote DeLanda (2011), such a mobile (scientific) assemblage

> is more likely to encounter novel situations than an immobile one. In this sense we may say that an animal that can move around and that can affect and be affected by a wider range of other entities is more deterritorialised than a plant that is tied to the soil.

The other way of looking at it, of course, is that architects should know their place and stay tied to their soil, that they shouldn't work undercover in the first place, that an architect operating within the walls of materials science is the wrong thing in the right space, and that materials science shouldn't put up with being infiltrated by agents from other fields. But as argued in Paper III, this spurious and synthetic separation between architecture, engineering, and materials science can be challenged. In Warhol (1975), genius pop artist Andy Warhol suggests that 'something funny' is bound to come out of such situations:

> I like to be the right thing in the wrong space and the wrong thing in the right space. But when you hit one of the two, people turn the lights out on you, or spit on you, or write bad reviews of you, or beat you up, or mug you, or say you're 'climbing.' But usually being the right thing in the wrong space and the wrong thing in the right space is worth it, because something funny always happens. Believe me, because I've made a career out of being the right thing in the wrong space and the wrong thing in the right space. That's one thing I really do know about.

The devil-may-care attitude of that quote seems to be echoed in Mitchell (1968), where Canadian singer-songwriter Joni Mitchell memorably delivers her laconic line about what life brings with it: 'Well something's lost, but something's gained/In living every day'. The present study grew from a conviction that while something might be lost from this kind of undercover operation, something else might certainly be gained. Maybe what is lost is an amount of faithfulness to the old, insipid patterns faithfully adhered to by researchers in architecture, engineering, and materials science alike, and what is gained is a prospective sea change in which things seem to naturally belong in new arrangements.

Now wouldn't that be *something funny?*

ACKNOWLEDGEMENTS

Some of the best acknowledgments this author has read are the interrogatory ones at the opening of Barad (2007), philosopher Karen Barad's controversial book *Meeting the Universe Halfway,* in which the author – a co-founder of the New Materialist movement, if such a thing exists – poses the question 'What does it mean […] to write an acknowledgment, to acknowledge or recognize contributors and contributions that help make something happen?' before going on to state that 'the past is never finished. It cannot be wrapped up like a package, or a scrapbook, or an acknowledgement; we never leave it and it never leaves us behind,' and even that

> There is no singular point in time that marks the beginning of this book, nor is there an 'I' who saw the project through from beginning to end, nor is writing a process that any individual 'I' or even group of 'I's' can claim credit for. In an important sense, it is not so much that I have written this book, as that it has written me.

The present thesis certainly wrote its author. It started out as a series of reflections on the value of 'the compromise' as a 'constructive conceptual tool' for the architectural design of multi-storey timber buildings, and ended (though indeed the past is never finished, and the conclusions herein will be continuously re-investigated and re-evaluated going forward) as an actual tool and a career-defining project that changed not only the way its author views the world around him and his place in it, but the very structure of the space of possibilities that governs his thought. Not the least, it gave him a hitherto lacking and much-needed combined conceptual and practical foundation upon which to base future studies of those spaces of possibilities that are capable of being actualised into buildings.

Since it is the author's belief that singular individual entities do exist in the actual world, his gratitude to some remarkable people and organisations of pivotal importance to the present undertaking should be expressed here. Carried out at the KTH Royal Institute of Technology in Stockholm, within the Division of Building Materials at the Department of Civil and Architectural Engineering, the thesis is a product of the EnWoBio (Engineered Wood and Biobased Building Materials Laboratory) research project, and was financed by Formas (the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, Project 2014-172), Svenska Träskyddsföreningen (The Swedish Wood Preservation Industries Association), and the KTH. Sincere appreciation for this financial support is gratefully acknowledged. Thanks to Mikael Westin and Fredrik Westin for a valuable collaboration.

The author would like to thank his main supervisor, Magnus Wålinder, and his co-supervisor, Andreas Falk, for intellectual and moral support, warm encouragement, knowledgeable contributions, and kind guidance throughout these PhD studies. Heartfelt thanks go to additional co-authors Roberto Crocetti, Martin Erlandsson, Alex Kaiser, and Ulf Arne Girhammar; to all (anonymous and non-anonymous) peer reviewers and editors; and to all the colleagues at the KTH, who made these years enjoyable and memorable. Thanks to all assistants through the years, in particular Jack Munro and Barthélemy Aupetit, who contributed to Paper I and Paper II, respectively. And thanks to Åsa Carild and Mattias Olsson for becoming the world's first AAA clients.

The author is also indebted to the principle developers of the software applications and plug-ins primarily used to assemble the design system at the heart of this thesis. A special thanks to David Rutten for inventing Grasshopper, but also to Robert McNeel, Daniel Piker, Timothy Logan, Robert Vierlinger, Mostapha Sadeghipour Roudsari, Chris Mackey, Michelle Pak, Konrad Sobon, Moethu, Mohammed Makki, Milad Showkatbakhsh and Yutao Song – and to the many incredibly helpful members of the Grasshopper3D and McNeel Discourse online forums – in particular Peter Fotiadis, Joseph Oster, Anders Holden Deleuran, Michael Pryor, Marc Syp, Tom Jankowski, and Hyungsoo Kim – who patiently and compassionately offered selfless guidance through all programming dilemmas.

The academic giants who in particular provided shoulders for this author to stand on are already highly present in the text to follow, but this being a work of synthesis, their more or less explicit contributions should be duly noted at the outset: Gilles Deleuze, Félix Guattari, Manuel DeLanda, John Frazer, Luisa Caldas, Hans-Jörg Rheinberger, Richard Feynman, Herbert Simon, Stuart Kauffman, Terrence Deacon, Graham Harman, John Holland, and Gregory Bateson: thank you for leaving behind tiny bits of uncharted territory in your meticulous explorations of domains adjoining and at times overlapping the one here studied.

In its more lucid moments, this thesis was produced by a specific assemblage that combined a human being, a computer, a pair of headphones, and rather loud music. Thanks to Dawn of Midi for *Dysnomia;* Four Tet for *a joy;* Kelly Lee Owens (and Radiohead) for *Arpeggi;* J. S. Bach, August Stradal, and Víkingur Ólafsson for *Organ Sonata No. 4, BWV 528: II. Andante [Adagio];* and Prince for *Sign o' the Times.*

Thanks to all amazing friends – too many to list here – and to the entire Larsson and Levy families for the generous and encouraging support along the way. Emmett, Astor, and in particular Madelaine somehow remarkably managed to put up with the author's silliness and sullenness throughout the writing of this thesis, providing love and affection way beyond what one might at the best of times expect from the assemblage known as a 'family'. As always, the sublime words of Jorge Luis Borges (1975) apply: *Being with you and not being with you is the only way I have to measure time.* Hopefully these pages might one day begin to answer your quite reasonable questions about what it was their author actually did for a living during those strange and magical years.

Magnus Larsson
Stockholm, October 2020

TRANSGRESSIVE CONNECTIONS: A NOTE TO THE READER

The theories that follow are of a multidisciplinary, interdisciplinary, transdisciplinary nature. This almost by definition means they constitute a *transgression,* a deviation from the norm, a crossing of borders meticulously erected between closely guarded disciplines, practices, and professions. Or rather: they establish new *connections* between artificially partitioned fields, branches of knowledge that are stubbornly viewed as discrete by academia but that simply cannot be separated in practice, where the three main areas of this thesis – architecture, engineering, and materials science – must come together to produce built structures.

As Rice & Littlefield (2015) declare, to transgress is

> to break, violate, infringe, or exceed the bounds of: laws, commands, moral principles or other established standard of behaviour. […] Transgression is an attitude within which one operates and crosses boundaries, challenging norms, risking censure, exploring hybridity and pushing beyond the periphery of established practice. […] to challenge, or go beyond, architectural codes, expectations and values is to challenge society itself.

Such behaviour rarely goes unpunished. Knowing this well, the present thesis doggedly insists on pushing beyond the periphery of the established doctrine and mapping out new transgressive connections. To what end? Because, as Rice and Littlefield go on to declare, a transgressive practice 'produces new forms of architecture, education, built environments and praxis'. This is the elementary motivation of the present thesis. If it succeeds in providing a model for the creation of such new forms, if it draws aside the curtain to expose such a hidden possibility, it will at least have lived up to the expectations of its author.

The model of the world presented here poses the existence of assemblages. We shall return to their definition shortly, but it may be noted here that an assemblage is defined not primarily by its component parts but by the relationships between those parts, the way they establish new connections – that is, by their transgressions. However, transgression always comes at a cost. As the old maxim from the field of construction has it, 'good work isn't cheap, and cheap work isn't good'. The cost to the reader here is threefold. The thesis breaks with the established norm by:

1) treating architecture, engineering, and materials science as part of the same dynamic and constructive assemblage, one capable of producing anticipatory adaptive assemblages.

2) introducing an array of concepts and neologisms. Key terms are listed below.

3) deviating from the conventional IMRAD structure (see the next section to follow).

These transgressions will be unacceptable to some readers, raising insurmountable obstacles and unassailable objections right from the outset. That is an unfortunate but unavoidable consequence of piercing the membranes that separate disciplines: some will feel as if their area of expertise has been violated. The ensuing disapproval is the cost to the author, who can only hope that the following sections, providing clarifications on terms and structure, will go some way towards mitigating the castigation his transgressions may induce.

THESIS STRUCTURE

This thesis contains four chapters, along with an introduction, a description of anticipatory adaptive assemblages (AAA), a background, a concluding discussion, and five appended papers. Readers unfamiliar with processes of evolutionary computation as a design strategy may wish to begin with the visual step-by-step guide to the creation of an anticipatory adaptive assemblage featured in the fifth chapter (Methodology), which provides an accessible introduction to the core procedures underlying the production of AAAs.

The conventional organisational IMRAD structure dominates academic writing in the sciences for a reason, perceived as a direct reflection of the process of scientific discovery. It is however less well suited for the synthesising nature of the present text, which interprets various theories, studies, and supplementary sources in order to position the appended papers within a greater body of knowledge, with the aim of producing an integrated theory that encompasses both philosophical underpinnings and pragmatic processes.

In an attempt to counteract the opinion stated in Slife & Williams (1995) that philosophical ideas remain largely hidden in scientific research, the thesis therefore deliberately deviates from the IMRAD norm, instead adopting an alternative structure perceived as better suited to the topic at hand.

Following the contextualising introduction, AAA description, and background, each chapter traces the argument put forward through the respective theories of ontology (being), methodology (practice), epistemology (knowledge), and axiology (values). The discussion seeks to bring these speculations together into a single, unified theory of the anticipatory adaptive assemblage: what and how it is, what the perimeters of our knowledge of it and the limits of its knowledge production might be, in what ways it could be created and controlled, and why it might be of value to us.

The thesis is written as a stand-alone text, with references to the respective appended papers where appropriate. The papers roughly connect to the theoretical themes as follows:

Paper I – ontology, methodology, axiology

Paper II – ontology, methodology, axiology

Paper III – methodology, epistemology, axiology

Paper IV – epistemology, methodology

Paper V – methodology, axiology

LIST OF PAPERS

This thesis contextualises the following five appended papers, which in the text are referred to by their corresponding Roman numerals:

I. Larsson, M., Kaiser, A., Girhammar, U. A. (2015) Conflict and Compromise in Multi-Storey Timber Architecture. arq: Architectural Research Quarterly 19(3):283–294.

II. Larsson, M., Wålinder, M., Falk, A. (2018) Teleodynamic Timber Façades. Frontiers in Built Environment 4(37).

III. Larsson, M. & Wålinder, M. (2020) Contextual Engineering of Materials: Optimisation of a Wood/Glass Wall Based on Weighted Objectives. Accepted for publication in International Wood Products Journal.

IV. Larsson, M., Wålinder, M., Falk, A., Crocetti, R., Erlandsson, M. (2020) Novel Processes for Architectural Optimisation of Building Materials Performance: Introducing Material Phase Transitions and Generative Life Cycle Assessments. Submitted for publication.

V. Larsson, M., Wålinder, M., Falk, A., Crocetti, R., Erlandsson, M. (2020) Sliding Sidewinders: Research Case Study of an Anticipatory Adaptive Assemblage. Submitted for publication.

The thesis can in some respects be viewed as an extension to a precursory licentiate thesis:

Larsson, M. (2014) Conflict and Compromise: An Evolutionary Framework for the Design of Multi-Storey Timber Buildings. Luleå: Luleå University of Technology (LTU).

Furthermore, the following published research contributions, presented at the respective conferences for which they were written, are also related to this thesis:

Larsson, M. (2016) COW – Parametrics Beyond Parametricism. In Andersons, B. & Kokorevics, A. (eds.) (2016) Proceedings of the 12th Meeting of the Northern European Network for Wood Science and Engineering (WSE). Wood Science and Engineering – a Key Factor on the Transition to Bioeconomy. 12-13 September 2016, Riga, Latvia, pp. 50–56.

Larsson, M. & Wålinder, M. (2017) Optimisation of Timber Structures based on Weighted Objectives. In Thybring, E. E. (ed.) (2017) Proceedings of the 13th Annual Meeting of the Northern European Network for Wood Science and Engineering (WSE), 28-29 September 2017. Copenhagen, Denmark, pp. 79–84.

SUMMARY OF PAPERS

Paper I (Larsson et al. 2015)

Architecture is defined as 'a conditional field of constantly varying parameters'. The role of the architect is to 'design compromises between these parameters'. The notion of 'compromise' is re-evaluated as a 'constructive tool' used to 'investigate the concept of "fitness" through evolutionary computation'. Several competing objectives (genes) participate in the creation of successful compromised positions (genomes), generating interesting and novel material and spatial organisations suspended between the controlled and the serendipitous. Using the Grasshopper and Galapagos plug-ins within the Rhino 3D application, the relationship between conflict and compromise is used as a strategic tool in the design of two multi-storey timber buildings, one that uses the Karamba plug-in to cull living units that perform a negligible structural role, the other incorporating optimisation algorithms that control the axial directionality of the building elements so as to create optimal conditions for the harvesting of renewable energy from its site.

Paper II (Larsson et al. 2018)

Leading on from the initial idea of genetically-controlled 'constructive compromises' outlined in paper I, a 'novel teleodynamic design tool called Contextual Optimisation Workspace (COW)' is introduced. Assembled within the Grasshopper environment, COW is then used to investigate how weathering-related site conditions may be allowed to inform the design process so as to improve a building's geometry, materiality, and performance. Deacon's theory of teleodynamics, a 'recent hypothesis about the way far-from-equilibrium systems interact and combine to produce emergent patterns,' is turned into practice and used to combine morphodynamic processes so as to allow the resulting design to reconstitute itself iteratively in relation to data from the past, present, and future. The tool is put to the test through experiments that materially optimise an urban timber façade: transmuting two grid systems into one, mitigating against photochemical degradation and wetting due to driving rain, and simulating illuminance to maximise the amount of daylight inside the structure.

Paper III (Larsson & Wålinder 2020)

Challenging an asserted artificial separation between architecture, engineering, and material design, the paper proposes novel protocols for mass-customised building materials, capable of making each material entity perform optimally at its given position within a geometry. It is theorised that the number of evaluated materials in an architectural surface should be expanded to become equal to its number of parts, and in turn that this number should be maximised given other constraints and objectives. Evolutionary design procedures could expand the built environment's conservative range of building materials to achieve additional performance targets. An experiment is conducted to investigate and develop two specific parts of the COW system's anatomy. New components add weights to objectives while punishing less favourable designs. The components guide the relative positioning of wood products within a single wall of an architectural structure, to achieve optimal performance given predefined targets. A path towards a 'contextual materials engineering technology' is discussed.

Paper IV (Larsson et al. 2020)

Through a leap of interdisciplinary abstraction, this paper discusses how the logic of phase diagrams – charts that plot differences in properties (such as volume) of a medium generated by changes in external conditions (such as temperature and/or pressure) – can be applied to produce material phase transition (MPT) diagrams, introduced here for the first time. Instead of charting the conditions for chemical equilibrium, MPTs are novel surface plots that reveal the relative benefits of a particular material system given a set of predefined objectives and a design space of potential solutions. It is shown that such diagrams can form an integral part of parametric design processes that use 'auxiliary loads' (e.g. LCA values) as variables to generate design iterations. A Grasshopper user object is created and used to design a box beam that yields a set of auxiliary loads charts and MPT diagrams. The anatomy of MPT diagrams is described, and areas for future studies discussed.

Paper V (Larsson et al. 2020)

The final paper is a qualitative and quantitative examination of an actual real-life implementation of meta-heuristic design processes in architecture. An examination of three digital experiments that were carried out by an architecture studio during the early design process of a building scheme, the report covers strategies to 1) reduce the meta-heuristic 'curse of dimensionality,' 2) explore how alternative geometries based on non-periodic tessellations of the plane might increase fenestration performance relative to a benchmark building, and 3) optimise a wall section through the use of MPT diagrams. These tactics yield a novel design framework, anticipatory adaptive assemblages (AAA), introduced here for the first time. AAAs simulate the effects particular combinations of material data yield in the context of a given design project, and are particularly effective in the early design stages 'when the potential to influence sustainability, performance, and life cycle cost is at its peak'.

CONTRIBUTION TO APPENDED PAPERS

The author's contributions to the work reported in the appended papers were as follows:

I. Larsson, M., Kaiser, A., Girhammar, U. A. (2015) Conflict and Compromise in Multi-Storey Timber Architecture. arq: Architectural Research Quarterly 19(3):283–294.

Larsson directed the conceptual work. Larsson and Kaiser carried out the architectural research assisted by Jack Munro. Larsson coordinated the work and wrote the article. Girhammar provided funding and guidance.

II. Larsson, M., Wålinder, M., Falk, A. (2018) Teleodynamic Timber Façades. Frontiers in Built Environment 4:37 (August 2018).

Larsson invented the concepts, carried out all of the modelling, programming, and research, and wrote the article. Wålinder and Falk provided guidance and expert feedback. Barthélemy Aupetit and Alex Kaiser assisted with the production of figures.

III. Larsson, M. & Wålinder, M. (2020) Contextual Engineering of Materials: Optimisation of a Wood/Glass Wall Based on Weighted Objectives. Accepted for publication in International Wood Products Journal.

Larsson invented the concepts, carried out all of the modelling, programming, and research, and wrote the article. Wålinder provided guidance and expert feedback.

IV. Larsson, M., Wålinder, M., Falk, A., Crocetti, R., Erlandsson, M. (2020) Novel processes for architectural optimisation of building materials performance: introducing Material Phase Transitions and Generative Life Cycle Assessments. Submitted for publication.

Larsson invented the concepts and programmed the MPT Grasshopper ecology. Larsson carried out all of the modelling and research, and wrote the article. Wålinder, Falk, Crocetti, and Erlandsson provided guidance and expert feedback.

V. Larsson, M., Wålinder, M., Falk, A., Crocetti, R., Erlandsson, M. (2020) Sliding Sidewinders: Research Case Study of an Anticipatory Adaptive Assemblage. Submitted for publication.

Larsson carried out all of the design work, modelling, programming, and research, and wrote the article. Wålinder, Falk, Crocetti, and Erlandsson provided guidance and expert feedback.

KEY TERMS

AAA	Anticipatory adaptive assemblage, a neologism invented by the author to designate assemblages with anticipatory and adaptive capacities. Pronounced ‘triple-A’.
Actualisation	The virtual is actualised during morphogenesis.
Adaptation	The process of change by which an entity becomes better suited to its context and environment.
Anticipation	The act of expecting or foreseeing something. Also the act of taking action in order to prevent or counteract something.
Assemblage	An identity-maintaining arrangement (Deleuze and Guattari: *agencement).*
Auxiliary loads	Materials-based variables beyond conventional loads, for instance LCA values such as global warming potential.
Axiology	Value theory. The study of the origin, nature, functions, types, and interrelations of values.
Capacity	A disposition that allows an assemblage to accomplish an entirely new actualisation.
Constraint	A value that acts as a restriction within prescribed bounds.
Contragrade	Deacon (2012): veering towards symmetry and order.
Definition	A non-anthropocentric term to replace Deleuze’s ‘machine’.
Design space	Feasible region. A diagrammatic representation of all possible solutions of an architectural MOO problem.
Desire	For Deleuze and Guattari (and by extension AAA), desire is not an imaginary force based on lack, but a real and productive force.
Disposition	Tendencies and capacities that are virtual (real but not actual) when not currently manifested or exercised.
Epistemology	Knowledge theory. The branch of philosophy that examines the nature of knowledge.
Evolutionary solver	Digital optimisation engine based on evolutionary principles.
Flat ontology	Concept introduced in DeLanda (2002b) to designate an ontology made exclusively of unique, singular individuals.
Form seed	The parametric geometry used in the construction of AAAs.

Genetic algorithm	Algorithm that applies evolutionary principles to find optimal solutions to an optimisation problem.
Grasshopper	A visual programming environment invented by David Rutten and developed by McNeel.
Homeodynamics	Deacon (2012): constraint equilibration and dissipation.
Hylomorphic	Aristotle: metaphysical view holding that every natural body consists of two intrinsic principles, one potential (primary matter), the other actual (substantial form).
Luminance	The light that illuminates a desktop so that we can see our work, the intensity of light reflected off objects and reaching the human eye.
Meta-heuristic	A higher-level procedure or heuristic designed to find, generate, or select a heuristic (partial search algorithm) that provides a sufficient solution to an optimisation problem.
Methodology	The study, theoretical analysis, and pragmatic use of a body of working methods: practices, procedures, rules.
Morphodynamics	Deacon (2012): constraint amplification and regularisation.
Morphogenesis	The generation of form. For AAAs: *digital* generation of form.
MPT diagram	Material phase transition diagram. A surface plot that charts the relative benefits of a particular material system given a set of predefined objectives and a virtual design space.
Multiplicity	A purely differential field. Deleuzean concept (adopted from Bergson and Riemann) replacing the notion of substance.
New materialism	Term coined in the 1990s for a realist cultural theory inspired by Deleuze, spurring a renewed interest in philosophers such as Spinoza and Leibniz, which criticises anthropocentrism and emphasises self-organising (non-human) processes.
Objective function	An algorithmic mathematical mechanism that minimises or maximises numerical values given constraints and objectives.
Ontology	The philosophical study of being.
Orthograde	Deacon (2012): veering towards maximum entropy.
Permutation	Mathematical term for the arrangement or rearrangement of a set. Used here as a synonym to ‘phenotype’.
PET	Parametric epistemic things. Concept introduced here for the first time: a digital ‘workbench’ experiment format.

Phenotype	Genetic term for observable characteristics (traits), but in a AAA context: an instantiated or actualised geometric design together with its associated data.
Pinwheel tiling	Non-periodic tiling of the plane featuring tiles in an infinite number of orientations.
Postponism	A philosophical concept introduced here for the first time: the act of postponing a decision for as long as possible.
Potential	Inherent capacity for development.
Presilience	A philosophical concept introduced here for the first time: the act of making something resilient before the fact.
Realism	Philosophical position posing the existence of a mind-independent world.
Resilience	Capability to recover from deformation and/or stress.
Teleodynamic	Deacon (2012): tending towards self preservation.
Tendency	A disposition that allows an assemblage to change what it is already doing.
Virtual	Real without being actual.
Voronoi diagram	A partition of the plane into regions close to each of a given set of objects (such as a finite amount of points in the plane).

ABBREVIATIONS & UNITS

2D	Two-dimensional
3D	Three-dimensional
AAA	Anticipatory adaptive assemblage
AD	Architectural designer (architect/engineer)
AEC	Architecture, engineering, and construction
ANT	Actor network theory
bar	Metric unit of pressure, equal to 100,000 Pa (slightly less than the current average pressure at sea level)
BM	Benchmark
brep	Boundary representation
BwO	Body without organs (Deleuze & Guattari)
CAD	Computer-aided design
CAH	Contact angle hysteresis
CAS	Complex adaptive systems
CIE	Commission Internationale d'Eclairage (International Commission on Illumination)
CLT	Cross-laminated timber
CO_2	Carbon dioxide
COW	Contextual optimisation workspace
DF	Daylight factor
DNA	Deoxyribonucleic acid
Ei	Illuminance due to daylight at a point on the indoors working plane
Eo	Outdoor illuminance on a horisontal plane from an unobstructed hemisphere of overcast sky
EP	Evolutionary programming
EPW	EnergyPlus Weather (file)
ES	Evolutionary strategies
FA	Fenestration area

FAR	Floor-to-area ratio
FEM	Finite element method
GA	Genetic algorithm
GH	Grasshopper
GLCA	Generative life cycle assessment
GSP	General simulation program
GWP	Global warming potential
h	Hour
H_2O	Water
IED	Integrated energy design
IR	Infrared radiation
ISO	International Organization for Standardization
k	Kelvin. The base unit of temperature in the SI
kN	Kilonewton
KPI	Key performance indicator
kWh	Kilowatt-hour
LB	Ladybug (a Grasshopper plug-in)
LCA	Life cycle assessment
lux	The SI-derived unit of illuminance, measuring luminous flux per unit area
m	Metre
m2	Square metre
MJ	Megajoule
mm	Millimetre
mm2	Square millimetre
MOO	Multi-objective optimisation
MPa	Megapascal
MPT	Material phase transition
mRNA	Messenger RNA

NE	North-east
nm	Nanometre
NW	North-west
OOO	Object-oriented ontology
P_c	Critical pressure
PET	Parametric epistemic things
PVC	polyvinyl chloride
R&D	Research and development
RNA	Ribonucleic acid
SE	South-east
SI	Système International (International System of Units)
SS	Sliding sidewinders; formal concept in Paper V
SW	South-west
T_c	Critical temperature
tRNA	Transfer RNA
UV	Ultra violet
WA	Wall area
WDR	Wind-driven rain
WWR	Window-to-wall ratio
xyz	Axes in Euclidean space
y	Year

CONTENTS

INTRODUCTION

1. INTRODUCTION

What common themes link the branches of architecture, engineering, and materials science? Each field could be characterised as focused on the art and science of the prospective. They are all disciplines primarily concerned not so much with what is or what was, as with what might be. They address some of the most pressing scientific, economic, environmental, social, and cultural problems of our time, and all three rely on the human desire and ability to manipulate and shape materials to fulfil our needs: quarrying stone to build a pyramid, calculating the most efficient steel structure for a bridge, positioning molecules to create an electrochromic window. That is, they are *material* sciences that base their respective tasks on means-end analyses, intended to establish the difference between an existing state and a desired state, and then find a correlating process that will erase that difference.

Following such an analysis, the typical architectural design process moves from form to structure to material. With Brier & Houdin (2008) and Parry (2005), we can imagine that a trailblazing architect, perhaps called Imhotep, envisions a unique step pyramid, consults a team of engineers to figure out how to make such a significant stone edifice stand up, and then orders quarrymen to excavate the rocks to build it. This conventional sequence suggests that materials are entirely devoid of agency, an idea with a long history that stretches back not only to Descartes and Newton but at least to Aristotle, whose theory of hylomorphism – the proposition that matter is formless and mush have form imposed on it to receive structure – has been formative to the Western world's thinking about materiality.

1.1 Hypothesis: evolutionary materiality

An alternative proposition would be that matter has an imminent agency. We shall return to fundamental procedures and mechanisms of material agency in section 4.6 below, when discussing the double articulation processes that for instance synthesise sedimentary rocks in nature, but for now it may suffice to say that one way of turning the conventional sequence outlined above on its head would be to use our growing knowledge about material properties, limitations, and capacities as objectives and constraints in a multi-objective optimisation operation aimed at generating an architectural form.

This area of multiple-criteria decision making is concerned with mathematical optimisation problems that involve the simultaneous optimisation of more than one objective function. A fenestration scheme that seeks to maximise window-to-wall ratio while minimising cost would be an example of a multi-objective optimisation with two conflicting objectives, but many more can of course be added.

The hypothesis guiding the present thesis is constructed from a three-tiered insight about architectural materiality: i) for the members of the AEC industry to not just decrease but begin to *reverse* their contribution to climate change, buildings need to be designed to be *energy positive,* and one of the shortcuts to such a development goes via the optimisation of the environmental impact of building materials, ii) such optimisations could be carried out within the context of evolutionary computation, using meta-heuristic processes (high-level procedures that generate and find sufficiently good partial search algorithms (heuristics), when the information is incomplete or the computation capacity limited) such as genetic algorithms (GAs), and iii) if a design framework based on such processes were created that endowed competing building materials with an agency – that is, gave the materials associated with an architectural geometry a generative capacity to influence that geometry by way of its associated quantified data and the result of simulations – that would entail an evolution of architectural materiality itself, potentially ending the sovereignty of the hylomorphic theory.

Despite not yet being established practice other than in a few specialist cases (usually involving firms with strong connections to academia), progress towards such an 'evolutionary materialism' design methodology could feasibly introduce a range of potential benefits, including the possibility for multidisciplinary design teams (incorporating the client) to be able to design more contextually appropriate, environmentally-conscious, future-proofed buildings by agreeing on a common set of objectives and parametrically sculpting knowledge (data) into optimised geometries, as shown in Figure 1. Contrasted with a conventional hylomorphic process, such a method has a better chance of finding optimal compromises between the conflicting interests among the stakeholders, but at a higher computational cost, as the evolutionary processes involved are of a complex and time-consuming nature.

1.2 State of the art

As discussed at length in sections 2.7–3.4 below, the above process is largely existent in various disciplines such as computer science and artificial intelligence – and to an extent also in architecture, engineering, and other design-related areas. Indeed, genetic algorithms make up the most prominent and widely used branch of knowledge within the collection of problem-solving techniques and algorithms that make up the field of evolutionary computation. DeLanda (2002a) noted, some 18 years ago, that the digital simulation of evolutionary processes was already a 'well established technique for the study of biological dynamics' and that one could 'unleash within a digital environment a population of virtual plants or animals and keep track of the way in which these creatures change as they mate and pass their virtual genetic materials to their offspring'. The hard work, wrote DeLanda,

> goes into defining the relation between the virtual genes and the virtual bodily traits that they generate, everything else – keeping track of who mated with whom, assigning fitness values to each new form, determining how a gene spreads through a population over many generations – is a task performed automatically by certain computer programs collectively known as 'genetic algorithms'.

As we shall see, DeLanda was in no way the first thinker to consider how buildings might be bred (or evolved) in a computer-based context, rather than designed in a more traditional way. But this prescient text, aptly titled *Deleuze and the Use of the Genetic Algorithm in Architecture,* is a precursor to the present work, and the method it employs – outlining three potential problems for designers wishing to use genetic algorithms, then answering them using three corresponding contributions from Deleuze – is antecedent to that used here.

Bäck (1986) introduces the theory and practice of evolutionary algorithms, Simon (2013) presents an updated approach to their basic principles, while Vikhar (2016) offers a critical review and discussion of their future prospects. Early work on evolution-inspired algorithms

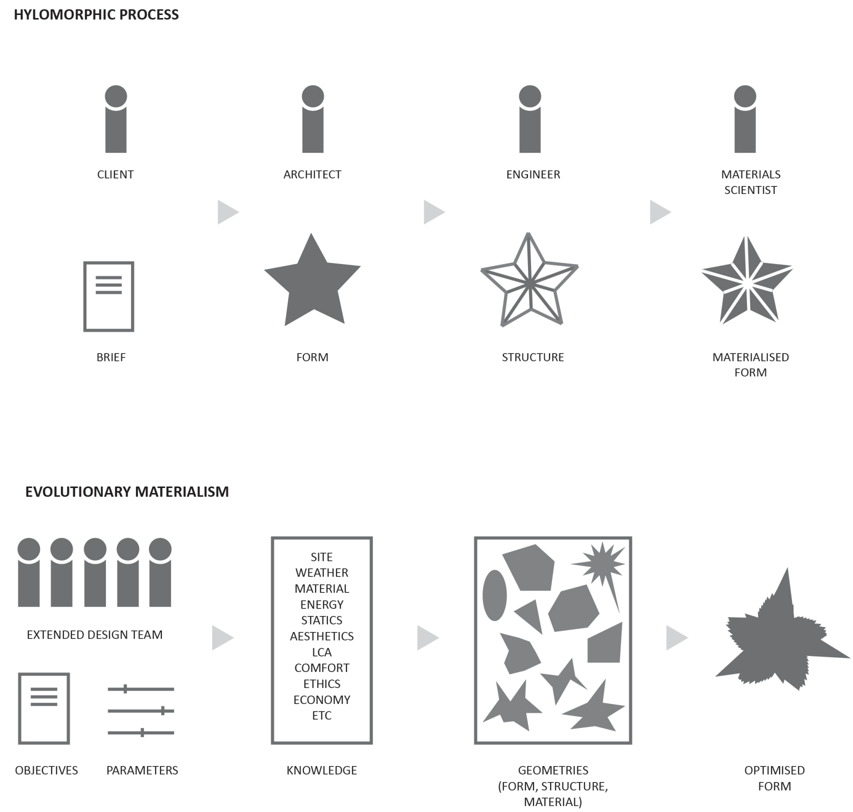


FIgure 1: Survival of the quickest or survival of the fittest? A traditional hylomorphic design process vs an evolutionary materialism methodology.

in the field of computational biology can be found in Fraser (1957), Fraser & Burnell (1970) and Crosby (1973); a collection of early papers is reprinted in Fogel (1998). Holland (1975) is arguably the groundbreaking work that put genetic algorithms (GAs) on the map. Mitchell (1996) and Michalewicz (1996) are good and readable general introductions to the topic, while Coley (1999), Haupt & Haupt (2004), Sivanandam & Deepa (2007), and Affenzeller et al. (2009) provide more scientific accounts of GAs. Goldberg (1989) is an informative book about GAs written by an engineer (with a PhD), while Kochenderfer (2019) presents a state-of-the-art overview of optimisation algorithms and their use in engineering. Papers such as Man et al. (1996), Tai & Akhtar (2005), and Sher et al. (2014) consider the application of genetic algorithms as a means to solve engineering problems. GA applications in materials science, including the engineering of building materials by way of genetic algorithms, is the topic of many papers, including Keser & Stupp (2000), Mahfouf et al. (2005), Coello &

Becerra (2009), Paszkowicz (2009), and Montemurro et al. (2012). A review can be found in Chakraborti (2004).

Frazer (1995), Kroner (1997), Caldas (2001), Caldas & Norford (2002), DeLanda (2002a), Fasoulaki, (2007), Besserud & Cotton (2008), Li (2012), Jing (2016), Latifi et al. (2016) and Zhu & McArthur (2020) are some relevant and instructive texts on the use of genetic algorithms in architecture. A far-sighted MArch thesis by Jones (2009) considers architecture as a complex adaptive system, with reference to the use of genetic algorithms as a design tool. Machairas et al. (2014) offer a review of algorithms for the optimisation of building designs, Nguyen et al. (2014) review different simulations-based optimisation strategies, while a relatively recent comprehensive literature survey on the use of genetic algorithms for building optimisation can be found in Li et al. (2017). Vincalek et al. (2020), finally, discuss why the uptake of GAs in industrial applications remains limited.

1.3 Academic domain

Paper V quotes the comparison made by Oliver (2014) of the energy required to support an area of flooring with building materials, and their related emissions, stating that

> a wooden floor beam requires 80 megajoules (MJ) of energy per square metre of floor space and emits 4kg CO_2. By comparison, a square metre of floor space supported by a steel beam requires 516MJ and emits 40kg of CO_2, and a concrete slab floor requires 290MJ and emits 27kg of CO_2.

This sensitivity to the environmental aspects of material performance has slowly percolated through the industry over the past half century or so: the author's copy of Everett (1970) scarcely mentions any climate aspects at all, apparently equalling 'sustainability' with 'longevity' in a way that seems unthinkable following WCED (1987) (the 'Brundtland report'). As Paper III states, the 'built environment's restricted material palette provides a limited space of possible combinations of material properties,' and evolutionary design procedures 'could expand this conservative range of materials to achieve additional performance targets'.

While this thesis seeks to establish connections, insufficiently provided in the existing literature, between recent theoretical advances and pragmatic processes that allow for alternative ways to design structures at the architectural scale, its agenda is first and foremost informed by the insight that the primary strategic imperative for today's climate-concerned ADs should be a focus on materiality in general and their materials´ auxiliary loads in particular. Such loads are defined in Paper IV as factors beyond traditional concerns about specifying building materials to achieve static equilibrium:

> Budgetary and legal constraints (the requirements set down in local design codes) are two obvious loads likely to affect the choice of material system, but it is easy to conceive of numerous others, including but by no means limited to environmental/ sustainability factors; programmatic and social considerations; weathering and maintenance aspects; aesthetic and phenomenological concerns; conceptual materiality; building performance; soil conditions and geomorphology; topographic

context; local weather conditions; resilience; even, as shown in Nyrud et al. (2014), psychological impact.

If we agree that auxiliary loads exist and if the above paragraph is taken seriously, two things become clear: 1) the asserted separation between architecture, engineering, and building materials science is an artificial construct; the three need to be brought together if, for instance, we are to achieve a design that is simultaneously optimised for aesthetics, weathering, and psychological impact, 2) few dedicated tools – processes and instruments – exist that allow ADs to create such multi-objective designs.

Objections are expected to arise as to why this thesis, written by an architect, is presented within the academic domain of building materials science, but the counter argument is this: the creation of material inventions, engineering solutions, and architectural compositions are not mutually exclusive operations but interconnected and interdependent means to the end of achieving the best possible built environment, including, as Paper IV states, the arguably mandatory requirement of 'having structures accomplish satisfactory building performance and efficient levels of operational and embodied energy'. As noted in Banham (1969), 'technological potential continuously runs ahead of architectural performance'. This thesis seeks to close the gap between the two by suggesting theoretical and practical ways to allow the different disciplines to inform and support each other.

While ADs such as Frei Otto and Bodo Rasch (1996), Neri Oxman (2010), Achim Menges (2015, 2016), Christopher Robeller & Yves Weinand (2016), and Philippe Block et al. (2017) have all proposed computational ways of endowing knowledge of material characteristics and logic with generative or form-finding capabilities, there is a gap in the literature with regards to theoretical aspects of this connection between materiality and adaptive form. Beginning to establish a model for why and how phenomena associated with materiality-driven architectural designs occur, and erecting a framework within which explanations of observed regularities can be positioned and new concepts constructed, is one ambition of this work. The new materialism movement is an exemplary, if obvious, candidate for such a construct, and the philosophical armature it provides is used to support the theories put forward here.

Le Corbusier (1925) proclaimed that 'an engineer should stay fixed and remain a calculator, for his particular justification is to remain within the confines of pure reason'. 95 years later, we know better. The invention of new methods and protocols that allow engineers, material scientists, and architects to cross-pollinate their domains will be key to effectively addressing future challenges that need to be confronted at the material level by the AEC industry.

1.4 Toolmaking

Such a development calls for dedicated tools that allow material data to be shared between disciplines and used in different contexts for different purposes. The materials we use to construct the world around us are of crucial importance to the built environment and its effect on the environment, but so are the tools with which we shape those materials and the mechanisms we use to design both the materials and their arrangements into built structures. As Kalay (2008) notes, architecture

> is a technology-intensive discipline. It uses technology – both in the process of designing and in its products – to achieve certain functional, cultural, social, economic, and other goals. In turn, technology transforms the discipline […] the adaptation of the Etruscan keystone arch enabled Roman engineers to build extremely strong and durable bridges, and led them to invent the dome as early as 27 BC. The invention of the Flying Buttress allowed 12th century Master Builders to replace the Romanesque's massive walls by the relatively thin and tall walls and soaring vaulted ceilings of the Gothic Cathedral. The invention of perspective and scale drawings in the 15th century radically transformed the practice and products of architecture…

John Gribbin (2001) notes that what is much more important than human genius to the progress of science is 'the development of technology, and it is no surprise that the start of the scientific revolution "coincides" with the development of the telescope and the microscope'. The fertile field where architecture and engineering intersect is now ripe for transition – just as astronomy and biology were in 1571 and around 1620, when those two devices were invented – and again, new tools are instrumental to the pursuit. Runberger (2012) argues that there is

> a great potential in allowing conceptual computational models to become the starting point for alternative processes of analysis and design, promoted as capable of enabling the encoding even of qualitative values.

In an attempt to harness this potential of analysis-driven conceptual design, the present thesis synthesises and reframes existing theories and software into a new tool, or framework, for the materials-based generation of evolutionary architecture. The creative energy and painstaking work that go into the development of new research tools is typically accompanied by high expectations of their usefulness, and the system presented here is no exception: ultimately, the hope is that this growing set of tools will help promote and guide the progress of a data-driven, material-sensitive built environment.

1.5 Aims and objectives

The aim of this thesis is to investigate and develop a framework for the transformation of material knowledge – properties and capacities at various scales – into generative mechanisms that can be used to optimise an architectural design for different loads and situations it may be subjected to during its life cycle, and have it adapt to its context. Secondary objectives include the development of a theory that anchors this conversion from material characteristics to architectural form, the invention of methods for using such transitions as part of multi-objective optimisation strategies within the context of materials-driven meta-heuristic architecture, considerations of how the new material and architectural knowledge produced by such processes may be used, and an exploration of different ways in which material data can be used as variables that have a direct and generative impact on the design of the built environment. The overarching question is this: what might be a valid framework for the use of building materials data, including simulation results, to optimise the design of architecture projects?

2. AAA

Everything is an assemblage. A molecule, a daydream, a Doric column, a metaphor, the city of Tokyo, a hurricane, the Chrysler building, Prince's seminal 1987 masterpiece *Sign o' the Times,* Charles Darwin's *On the Origin of Species*, a cup of coffee: all assemblages. That is, they are all *arrangements*, entities that through extrinsic relationships combine heterogenous parts into new compositions. Those parts are themselves assemblages, all of which have an individual identity shaped by a particular historical process – a moment of birth, a moment of death, and in between the two some sort of interval. When the parts are brought together, the properties of the resulting assemblage are more than the sum of its parts: a cup of coffee is something more than just roasted coffee beans and water. This means the assemblage is *emergent,* irreducible to its parts.

While everything is an assemblage, this thesis holds that a particular kind of assemblage has a remarkable potential to help optimise the built environment and support its crucial transition from being a net consumer to becoming a net producer of energy. Its author invented the neologism 'anticipatory adaptive assemblage' (abbreviated AAA, and pronounced 'triple A,' hence typically preceded by the indefinite article 'a') to designate such an assemblage, a special kind of information-carrying architectural geometry endowed with anticipatory and adaptive capacities. AAA is the author's attempt to explore the hypothesis put forward in section 1.1. While a mapping of the anatomy and mechanisms of a AAA is the topic of the entire thesis, this chapter's brief summary of its core premises and key terms might serve as a preliminary introduction.

The rest of this chapter is structured as follows: The AAA process is described from form seed to algorithm termination. An initial connection between AAA and contemporary realist philosophies is made, and the methodological shift at the heart of the thesis – a progression from subtractive design processes yielding single buildings to evolutionary processes yielding populations of buildings – is described. The foundational principle, basic principles, and disruptive potential of AAAs are discussed, together with the idea of moving beyond the mimetic methods of biomimicry to the systemic methods of evolutionary design. AAA's potential to explore and exploit systemic forces is shown to peak in the early stages of the design work. Finally, with a nod to Perec (1974), the fundamental task of the AD is reformulated to become the designer of species of spaces.

2.1 The AAA process

The AAA model is based on a 'form seed,' a computational geometry that is *parametric,* possible to differentiate by way of parameters (streams of in data). Imagine one of the equaliser units typically found in old analogue stereo systems, the kind that features drawbars and knobs. Now connect this imaginary control unit to a computer, and consider each control (which following a biological analogy we may call 'gene') as being capable of influencing an on-screen geometry: pull a drawbar up, and the height of a box-like form on the screen increases, turn a knob and the box rotates. Now envisage the box as being physically situated somewhere in the world, a position that brings with it particular local weather conditions. We use databases to map this local weather, then simulate for each hour of the year the solar radiation falling on the surfaces that make up the box. Every time we change the setting of a knob or drawbar, we record as out data the particular combination of control settings (the 'genome' of the form), together with the radiation values and total volume of the box produced.

Since pulling drawbars, turning knobs, and recording out data is a tedious undertaking, we instruct the computer to do it for us. Furthermore, we tell the computer to change settings a certain amount of times (producing a 'generation' of forms; all generations added together making up the entire 'population' of generated forms) and then measure the *performance* – the combination of volume and surface radiation (the 'fitness') – of each form ('individual,' 'phenotype,' or 'assemblage') produced within this generation. Adding genetic algorithms (a family of search algorithms inspired by the principles of biological evolution) to the system, we force it to evolve toward better-performing solutions by starting from a population of randomly generated individuals and then selecting the more fit individuals in each generation to form the beginning of a new generation, while modifying those promoted individuals' genomes through processes (such as recombination and random mutation). We terminate this algorithm at some predetermined point, for instance when a maximum number of generations has been produced, or when a satisfactory fitness level has been achieved for an individual or a generation.

For the sake of clarity and perhaps modesty, three things should be noted right at the outset: 1) The AAA acronym was invented at the time of writing Paper V, and up until that point, the 'design tool' that produced what was in effect AAAs was called COW (contextual optimisation workspace). This thesis uses the AAA denomination as an umbrella term for the theory, method, and outcome of AAA processes; 2) As clearly stated in Mayr (1982), 'all hypotheses are tentative,' and this one is no exception: AAA theory must be forever tested and revised if found to be unsatisfactory, and future changes to the theory 'is not only not a sign of weakness but rather evidence for continuing attention to the respective problem and an ability to test the hypothesis again and again'; 3) The acronym is used interchangeably across different spatio-temporal scales. AAA may thus refer to the entire AAA theory, to the population of virtual (explored or unexplored) design iterations made possible by a AAA, or to an individual design arising from that AAA.

In line with the contemporary philosophical armatures upon which it moulds its arguments – including the new materialism, speculative realism, and object-oriented ontology movements – AAA is based on an unequivocally *realist* view of the world. This has several implications, chief of which is probably that it assumes the external world to be existing independently of human awareness. As Harman (2017) puts it, this 'cuts against the grain of the past century of continental philosophy, and leads in directions surprisingly alien to common sense'. The title of this thesis is a play on this connection to the 'neo-materialist' school of thought, a sort of 'reinvigorated' materialism spearheaded by a diversified body of contemporary theorists including Manuel DeLanda, Rosi Braidotti, Donna Haraway, and Karen Barad. New materialism is described in van der Tuin & Dolphijn (2010) as

> a cultural theory inspired by the thoughts of Deleuze, that spurs a renewed interest in philosophers such as Spinoza and Leibniz, shows how cultured humans are always

> already in nature, and how nature is necessarily cultured, how the mind is always already material, and how matter is necessarily something of the mind.

From this position, the thesis explores the *modus vivendi* of certain material aspects of architecture and engineering, particular arrangements that allow conflicting objectives to peacefully coexist (solidify in the virtual or actual sense), either indefinitely or until a final settlement is reached (the representation and/or construction of the material assemblage we call a building).

It is an attempt to formalise, quantify, and modulate the largely invisible structures – from zoning ordinances via aesthetic preferences to levels of CO_2 emissions – that control, or suspend, a design at the architectural scale. It does so by first defining the different capacities of a scheme's constraining variables (the extent to which they can effect possible geometric modulations), and then digitally testing the outcomes of multiple combinations and interactions of those variables, allowing a design to be bred and evolved as a result of a series of simulations and differentiations based on historical or projected data.

That is to say, it propounds a profound methodological shift: from the notion of a singular building being the result of an essentially subtractive traditional design process (the AD repeatedly decreasing a design's axes of freedom until it reaches a final stage where no further reductions are made) to that of an architectural design being a single actualised instance within a vast multitude of virtual iterations produced by an evolutionary process driven by genetic algorithms (Turing 1950, Mitchell 1998) and simulations. As shown in Steadman (1979), at a basic level, this is not a new idea: evolutionary thinking has had an impact on architecture at least since the 1860s.

2.2 General Architecture and the foundational principle

Practitioners within the fields of physics and philosophy share a common dream: that of inventing a unified 'theory of everything'. As Barrow (2007) relates, such dreams 'are not new; Einstein wasted the latter part of his life in a fruitless and isolated quest for just this Theory of Everything'. This is not so strange given that the idea indeed originated with Einstein, as Gribbin (1998) declares:

> The idea of finding one mathematical description which would include all of the forces of nature has been the Holy Grail of physics from the moment Einstein came up with a field theory of gravity, the General Theory of Relativity.

Tegmark (1998) explains this as 'an all-embracing and self-consistent physical theory that summarizes everything that there is to know about the workings of the physical world'. However, physicists and philosophers do not talk about the *same* theory, or even about the same 'everything'. While physicists pursue a descriptive theory of nature, one that describes how the world works, philosophers search for a metaphysical and/or normative theory, one that explains why there is anything at all, how reality can be understood, and how we should live our lives within it. As Fox (2006) points out, what physicists actually mean by such a 'theory of everything' (or General Physics, as he thinks it should more humbly be called) is

> not a theory of everything, period, but a theory that lies at the basis of all things physical: a unified (descriptive) theory that can satisfactorily account for the widest possible range of physical phenomena.

Fox proposes the aligned term General Ethics to describe 'a theory that lies at the basis of all things ethical: a unified (normative) theory that can satisfactorily account for the widest possible range of ethical concerns'. The jury is out on whether his endeavour is successful, just as it is on whether there is a 'final theory of everything' waiting to be discovered. English (2017) certainly does not believe this to be the case:

> No theory, however potent, could in one fell swoop explain away the complexities that arise across different scales or predict the nuances that present themselves in various observational contexts. The idea that such a theory may be just around the corner is incompatible with notions of emergence that science itself has uncovered.

What can be said for sure is that to date there is no General Architecture, no 'theory of everything' for the built environment, no supposition that satisfactorily accounts for the widest possible range of architectural and engineering concerns. But if there were such a theory, or if, following Fox and for the sake of argument, we were to attempt to construct one, it would arguably need to be based on a firm conviction of what architecture and engineering are centrally concerned with, which foundational principle they answer to. Even before we begin to search for such a principle, we already know some of its properties. It seems clear that the principle should have bearings on what we think constitutes architecture, which fundamentally is a question about how we understand reality and the notion of 'being'. It must provide us with some idea about what truth is and how knowledge might be obtained, which Harman (2017) tells us is particularly hard

> in fields such as the arts and architecture, which are governed by shifting currents of taste rather than by calculative formulae: a difference that has mostly served to devalue these fields in the public eye in comparison with those that seem to produce actual knowledge, such as science, engineering or medicine.

(Note the proposed wedge – imaginary as far as AAA is concerned – that Harman attempts to drive in between architecture and engineering.)

Furthermore, the principle must not only support a theory, but be readily applicable to the real-world act of designing architecture. And finally, it should position architecture within a value-based system capable of responding to our continuously growing knowledge of what implications and effects the design of our built environment has on a wide range of aspects including economic, social, and environmental sustainability and potential.

In other words, the principle should at the very least point towards or encompass the possibility of constructing a conceptual quartet that includes an ontological assumption, a pragmatic methodology, an epistemological model, and an axiological position. All of these areas would be grist for the mill of a General Architecture theory, and while we are not necessarily pursuing a potentially 'fruitless and isolated quest' for such a grand and unified theory, we are interested in providing an integral framework for the production of evolutionary architecture, and explaining how AAA functions within these four domains is the topic of this thesis.

The foundational principle at the heart of AAA is, unsurprisingly, that architecture is fundamentally an assemblage endowed with anticipatory and adaptive capacities. AAA's provocative summary of its subject matter is this: form follows fitness, and architecture is the best possible compromise between the different predilections of its design team (which may be composed of a single creator or an extended multitude of specialists), given the context within which it is situated.

2.3 AAA: basic principles

Designing anticipatory adaptive assemblages is a pragmatic method for creating a particular type of architecture, one that comes with a diversified background, a theoretical dimension that seeks to be as capital-g General as possible within the confines of its practical-conceptual demarcations, and a promising future to boot. The latter will be explored in the Discussion chapter, while a brief recollection of its historical background will be offered in sections 3.3–3.4 below.

Some of the basic principles of AAA, to be visited in detail in the coming chapters, are as follows: 1) Any architecture is always the compromised outcome of a range of (usually conflicting) desires modulated by constraints, 2) Such desires and constraints can be mapped as a design space or fitness landscape ripe for productive exploration (the GAs adapting the system to its constraining parameters) using artificial intelligence techniques such as evolutionary computation, 3) Architectural assemblages (emergent wholes composed of autonomous parts, irreducible wholes produced by relations of exteriority, further explained in section 4.2 below) within this fitness landscape, roughly corresponding to phenotypes in the correlated biological metaphor, feature parametric controls capable of carrying different variables, have a fully contingent historical identity, and thus share ontological status (as 'individuals' of the same 'species'), 4) The architectural assemblage is always composed of heterogenous components (an 'environment,' or 'contextual frame,' made up of elements such as site, brief, weather, and legal restrictions). Even what Blanciak (2008) refers to as a 'siteless' building is conceptually situated on a dimensionless point, as if its 'site value' were set to zero, 5) There are precisely two *modes* of architecture: virtual and actual, actualised (actually constructed) individuals making up our visible built environment 6) Combining machine learning with simulations, the AAA assemblages have a capacity to *anticipate* possible futures, 7) Finally, this anticipatory capacity bestows upon the assemblages an adaptive capacity, including the potential of 'learning' by feedback-induced self-regulation.

2.4 Disruptive AAA

AAA can on the one hand be viewed as a simple (if non-obvious) concept that explains a diverse and complex set of phenomena. On the other, it may be criticised as being an example of architectural scientism and sophistry, a pretentious and utterly cosmetic application of science and philosophy to the built environment that complicates the process of designing and engineering buildings at best, and promotes glittery frauds such as greenwashing at worst. However, as we shall see, AAA is not simply a technocratic method

FIgure 2: Le Corbusier's famous 'five points' of architecture – pilotis, free plan, free façade, longitudinal windows, and roof garden – hardly answer to contemporary demands such as optimised energy performance and material sustainability. (Lev Manovich)

for turning building science metrics into the yardstick of successful architecture (though such metrics *can* indeed be used as objectives if desired and/or required). Rather, it corresponds to the assertion about philosophy in Harman (2017), as being a 'potentially disruptive force, with a vastly different agenda for human advancement than the sciences'.

This is because of the fundamentally (methodologically and axiologically) *agnostic* relation between AAA as a method/theory and the variables fed into a design tool based on AAA: the anticipatory adaptive assemblage will happily turn any adequate and quantifiable set of input data into generations of geometries with associated output data. If an AD with a sinister agenda wished to optimise, for instance, the fascist qualities of an assemblage, and if a quantifiable variable controlling such qualities existed, AAA could in principle be used for this nefarious activity (anyone interested in pursuing such a highly dubious undertaking may wish to consult the distinguished analyses featured in Eisenman (2003), not that this author endorses such atrocious schemes).

What this admittedly tongue-in-cheek remark shows is that one of the most significant advantages of evolutionary processes is their inherent flexibility and adaptability to the task at hand, combined with robust (if usually slow) performance. As Bäck et al. (1997) note, 'evolutionary computation should be understood as a general adaptable concept for problem solving, especially well suited for solving difficult optimization problems, rather than a collection of related and ready-to-use algorithms'.

If the above appears to call into question many of our basic assumptions of what architecture is and does and might one day become, it is because it *does*. To begin with, this brief outline immediately calls for a radical redefinition of the role of the architect, which, as we shall see in the next section to follow, repositions the profession's practitioners rather far away from the traditional stereotype of an uncompromising middle-aged balding white man peering out from behind black-rimmed spectacles, complacently mumbling about the unrivalled virtues of *pilotis* and longitudinal windows.

2.5 The limitation of imitation

Let us pause for a brief moment to consider the background we have outlined for this necessary redefinition. The concept of AAA, while perhaps not a full-blown theory of General Architecture, presents an opportunity to consolidate theoretical underpinnings with pragmatic design processes and provides a unified system for the creation of evolutionary architecture. What new requirements does this demand with respect to the design team?

Maybe not so many. It just makes the existing requirements more explicit. The act of designing a building has always been an inherently multidimensional process. While the outcome of the AAA design process is an extensive series of virtual and occasionally actual objects in three-dimensional space, the process itself typically occurs within a massively high-dimensional mathematical problem space, in which each individual design decision forms a dimension. These dimensions correspond to the 'degrees of freedom' that define the realm of possibilities within which the assemblage is being designed. The simplest way to envision this might be to think of the assemblage as a complex maze in which each forking path represents a decision to be made: choose variable A and turn left, or choose variable B and turn right. The entire network of paths and corridors make up the 'design space' of the assemblage, a single path through the maze represents a 'genotype,' and the final path chosen corresponds to a single individual assemblage, a 'phenotype'.

Designing a building inescapably calls for a multitude of such decisions to be considered, over and above its shape in three dimensions. To continue our thinly veiled (and perhaps diachronically unfair) critique of Le Corbusier (1923), a mere 'five points' (Figure 2) hardly suffice to answer all the necessary questions that need to be raised about details such as the building's formal composition, materiality, structure, construction, energy use, compliance with regulations, response to site-specific features such as topography and weather, budgetary restrictions, LCA targets, programmatic requirements, and so on. A full enumeration of all possible combinations of decisions would yield a massively high-dimensional design space featuring an enormous number of possible assemblages.

Again, this was always the case. The Swiss-French architect of course knew that his five points did not tell the whole story; he just chose to disregard the other dimensions of his design space. This is a common strategy, as humans are badly equipped to imagine or understand spaces beyond the three or four dimensions of our everyday surroundings. As ADs, rather than attempting to navigate through a highly complex, multi-dimensional space of possibilities, we opt to break down the overarching design challenge into smaller and more manageable parts that can be considered individually. However, this means decisions are made without a full understanding of their impact on other aspects of the design: those

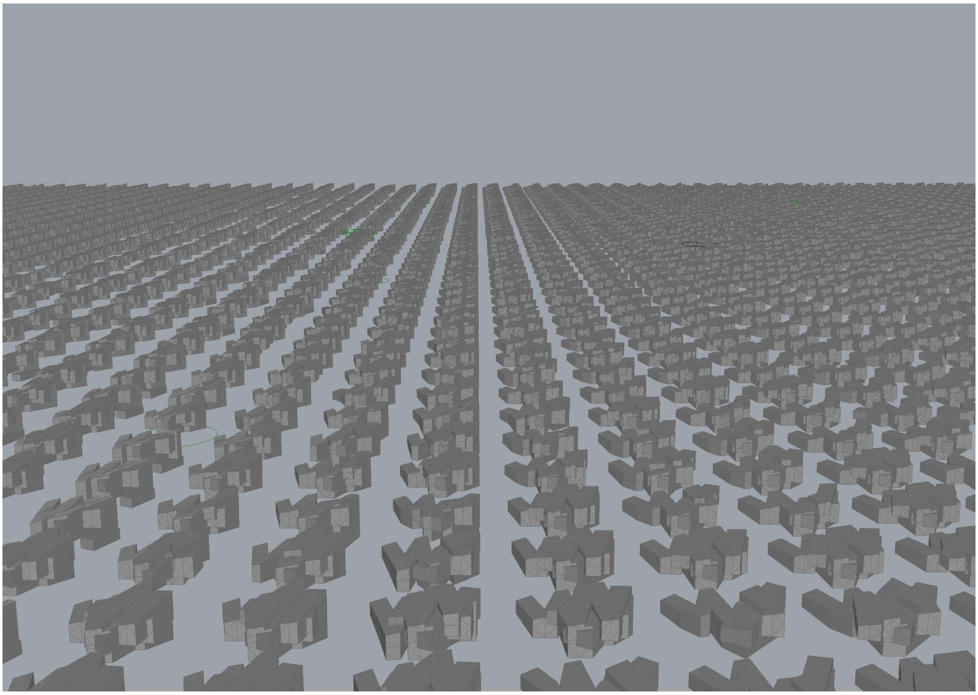


FIgure 3: Quite a few more than 'five points' – a small subset of the geometries, all subtly different variations on the same theme, composing the design space explored in Paper V.

longitudinal windows may for instance be nice to look at (or out of), but let in too little light or too much solar radiation. Unless we simulate the effects of different window dimensions or entire fenestration schemes on the actual façade and site in question, we will have a hard time knowing for sure which is the optimal alternative. Le Corbusier's steadfast belief in and promotion of the axioms of his own invention are in some ways impressive, yet quite hard to reconcile with contemporary demands on building performance (and associated ethical considerations). How does one justifiably resolve conflicting objectives without pitting alternative options against each other and evaluating the outcomes?

This inflexible and dogmatic adherence to simplistic manifestos so typical of the Modernist movement produced many canonical buildings that appear to be indisputably beautiful, but that also, a century later, seem strangely lacking in terms of values plotted along other vectors than those representing aesthetic considerations and rule-based theoretical constructs, and more often than not fail to connect to their sites. Now compare those authoritative buildings to the forms designed in nature: a stupendous range of variations uniquely adapted to the requirements of their immediate environments and highly performing within their respective contexts.

Designers drawing inspiration from nature have too often ended up promoting some version of biomimicry, which its most staunch advocate describes in Benyus (2002) as 'a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems'. But while allowing the design of, say, a solar cell to be inspired by the shape of, say, a leaf may – or may not – be a reasonable design tactic, moving beyond such a reproduction of physical forms found in nature to instead focus on adopting nature's design *method* is arguably more likely to yield successful outcomes. The shape of the leaf is a product of evolution; by modelling the processes underlying its development, we can design myriad variations on the theme of the single leaf, and see which of them suits our purposes the best. This is a theme running through all five appended papers – Figure 3 shows a small part of a population of geometries evolved in Paper V.

Nature designs by way of evolutionary processes. In nature, as we know from Darwin (1859), though he did not put it in so many words, *form follows fitness* – the common characteristics of all individual members of a species evolve over time through the process of natural selection, a reproductive process that continuously improves the species through adaptation to the environment and interaction with other species. Blackmore (2013) describes this as a simple three-step algorithm that

> explains, with one simple idea, why we live in a universe full of design. It explains not only why we are here, but why trees, kittens, Urdu, the Bank of England, Chelsea football team, and the iPhone are here.

The three steps of this genetic algorithm are 1) selection (all members competing for resources, with only the fittest surviving), 2) breeding (survivors reproducing to create new offspring that share some of their characteristics), and 3) mutation (some of the offspring's characteristics randomly changing). (Mayr (1988) goes one step further, proposing that evolution in essence is a two-step process of random variation and selection, but to this author, keeping mutation separate seems appropriate.)

Let us pause for a moment to probe a little deeper into the logic and mechanisms of GAs. Based on the ideas of natural selection and genetics, these adaptive search algorithms were invented to intelligently direct the search for optimal solutions into regions of better performance within the design (solution) space, and are commonly used to generate high-quality compromises between conflicting objectives.

Using evolutionary solvers in Grasshopper (GH), the AAA simulation of the 'survival of the fittest' mechanism works as follows: a large population of individuals is generated, subdivided into generations, by automating the process of changing slider values that control a form seed. Each such slider value represents a 'gene,' and every combination of genes (data) a 'chromosome' (set of parameter values). An individual's corresponding 3D model is called a phenotype. Each such individual (phenotype) is given a fitness score that shows its ability to 'compete'. The algorithm searches for the individual with the optimal fitness score (or the one nearest the optimal score).

Each generation thus consists of a population of individuals, and each individual represents a possible solution (a point) in the algorithm's search space. The initial generation is randomly generated. Following this, each successive generation becomes increasingly better suited to its environment, as the 'fittest' (most successful at adapting to changes) individuals are selected to mate (combine parent chromosomes) and produce better offspring. This process uses three operators: i) selection (preference is given to individuals with good fitness scores), ii) crossover (mating between individuals: crossover sites are chosen randomly, and genes at those sites are exchanged, creating a new individual), iii) mutation (genes are inserted randomly to maintain diversity in the population).

As the generation size is kept static, some individuals will die and be replaced by new arrivals until all mating opportunities are exhausted. Over successive generations, better solutions arrive as worse ones die off. On average, each new generation thus has more 'better genes' (better 'partial solutions') than previous generations. Once there is no significant difference in fitness between a new generation and the previous generation, the algorithm is said to have converged to a set of solutions to the problem.

We shall return to the idea that form follows fitness in section 4.7(v) below. For now, it may suffice to note that throughout this algorithmic process, breeding and mutation operate on the *genotype* – the DNA that encodes all information the organism is based on and guides its lifelong development – while competition and selection operate at the level of the *phenotype* – the physical expression of the organism, which combines the genotype with the organism's lifelong interaction with the environment in which it lives.

Natural evolution takes place across immense time scales. Using the mathematical concept of optimisation, our redefined AD can, however, use the logic at the heart of evolution and apply it to a design process. Different methods for achieving this will be discussed and explained in further detail in chapter 5. For now, suffice to say that the AAA architect aims to find the combinations of input data that best satisfy the relevant objectives while working within the limits of the constraints of the design space. This process mirrors the one found in nature, where natural selection 'tries' to produce new individuals that better fit the objectives and constraints defined by their environment. Simplifying the more in-depth explanation above, the three-step algorithm of evolution can now be translated into a computer-based design process that 1) generates phenotype assemblages inside a delineated design space based on a parametric 'form seed,' 2) evaluates each phenotype's performance using some relevant set of metrics, and 3) evolves the system using evolutionary algorithms that search through the design space to find the most high-performing assemblages and allow them to reproduce.

We can now see that the architect's task has ceased to be that of a demagogue defending longitudinal windows or leaf-looking solar cells, to instead become that of the creator of an entire species of assemblages. The architect no longer designs a single physical object (a single individual, or phenotype), but rather designs a form seed capable of producing that single physical object, and many variations on the same theme. The form seed is a parametric system that encodes the full range of forms possible to produce within the design space. This could be done using any parametric modelling software that allows a set of parameters to drive a series of geometric operations that in turn produce the final forms; in this thesis, the Grasshopper software is used.

The AAA architect proceeds to design elegant constraining functions that push the system as far away as possible from the impossibly slow brute force method of analysing every

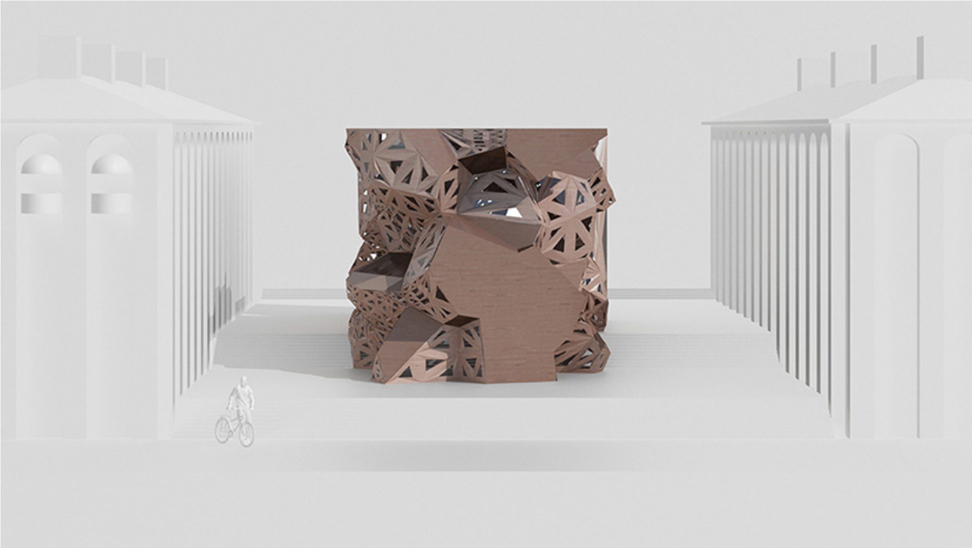


FIgure 4: An example of a final AAA geometry – an individual, or phenotype – as developed in Paper II. The role of the architect is redefined, following Gordon Pask, to catalyse buildings, act that they may evolve.

phenotype possible within the design space, taking full advantage of the algorithmic power and machine learning capabilities presented by evolutionary computation. As famed cybernetician Gordon Pask memorably summed up the new task at hand in Pask (1995): 'The role of the architect here, I think, is not so much to design a building or city as to catalyse them; to act that they may evolve. That is the secret of the great architect'. Having left the computer – typically for a substantial amount of time – to run the calculations, produce the phenotypes, and analyse the associated data, the final (and considerable) task of the AAA architect is to use the a wide and growing variety of methods at his or her disposal to search through and select a final assemblage, usually among tens or hundreds of thousands, to be actualised into a built structure.

Paper II is a good example of how an architect might catalyse buildings, act that they may evolve. The architect's role in the AAA process described in this paper can be summed up in five steps: 1) construct a form seed based on some concept or contemporary theory (this could be virtually anything but in this case was the teleodynamics theory developed by biological anthropologist Terrence Deacon, which provides a constructive and generative set of mechanisms that can be used to conceptualise a geometry into being), 2) use this form seed (and its underlying theories) to produce a final geometry (individual/phenotype; shown in Figure 4), 3) subject this final form to experiments that investigate strategies for minimising material degradation and maximising the building's material durability, 4) subdivide the façade surfaces and allocate a range of different surface panels made from varying material combinations based on materials-driven logics, 5) conceptually tie the project together by devising a fenestration scheme based on the same teleodynamic concept as that driving the underlying architectural form.

2.6 Exploring and exploiting systemic forces

This idea of the form seed constituting a 'system' relates the AAA model to the history of Systems Theory, which is conventionally viewed as beginning with Austrian biologist Ludwig von Bertalanffy's theoretical writings on 'organismic biology' in the late 1920s – see von Bertalanffy (1928) and Hammond (2003). In von Bertalanffy (1972), however, the thinker stated that 'the notion of system is as old as European philosophy,' and traced its development from pre-Socratic times via thinkers like Aristotle, Leibniz, Hegel, and Fechner to the modern day.

In his *tour de force* through the topic of architectural design methods, Philip D. Plowright (2014) insists that the highly influential French architect Eugène-Emmanuel Viollet-le-Duc (1814–1879) introduced the idea – albeit without the use of contemporary terminology – to the field of architecture already in Viollet-le-Duc (1873), almost half a century before Bertalanffy. This book, *The Story of a House,* is a narrative of an experienced architect walking his 16-year-old cousin Paul through the design process for realising a house for his sister, Marie. As recounted by Plowright (2014):

> In the process, Paul is taught to construct a programme for a client; examine the siting of the building for positive and negative qualities; arrange rooms for mutual advantage; consider view and light as aspects of interior space; construct a plan-based composition of all the formal elements; project a plan into a section in order to consider roof geometry; and, finally, construct elevations which are based on programmatic need.

According to Hearn (2003), Viollet-le-Duc was 'the first to articulate a comprehensive theory of design method'. And *The Story of a House,* claims Plowright, is the beginning of one out of three major methodological frameworks found in architectural design, namely that of force-based design. (The two others – based on patterns and concepts, respectively – are beyond the scope of the present thesis). In Plowright (2014), examples of practitioners that have utilised this force-based design framework include not only Viollet-le-Duc, but also luminaries such as Louis Sullivan, Sullivan's disciple Frank Lloyd Wright, and Christopher Alexander (by way of Scottish biologist and mathematician D'Arcy Thompson's morphological studies in the early 1900s), as well as several contemporary offices: 'OMA and its various offshoots – including REX, Foreign Office Architects, MVRDV, WorkAC, MASS Studies, Studio Gang, and BIG'.

Groák (1992) developed the force-based design methodology into a view of architectural structures as fluctuating arrangements in dynamic environments, claiming it is useful to 'see buildings as "unstable systems," ones which sometimes cannot respond quickly enough to their changing circumstances – whether it be internal comfort, environmental degradation, new social or economic conditions or the external climate'. We shall return to this idea in the Discussion chapter. For now, let us simply note that the basic tenet of force-based systems is the belief that architectural form is 'the direct manifestation of forces, flows, or pressures,' and that 'identifying these pressures through the introduction of a series of constraints and assets allows decisions to be negotiated, moving towards a final proposal'.

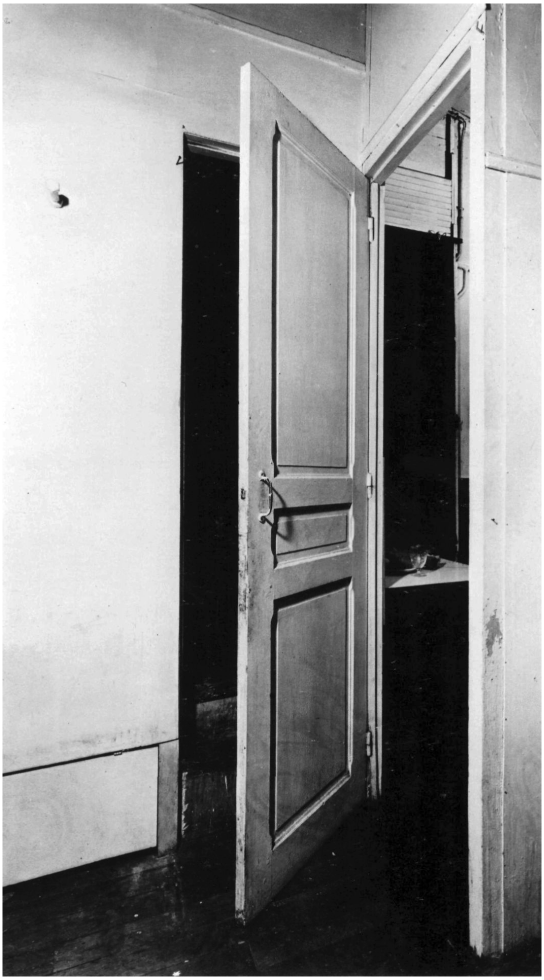


Figure 5: The door in Marcel Duchamp's studio at 11 rue Larrey, Paris. Opening one door closes the other: a physical implementation of the idea that exploiting one strategy might make other explorations unattainable. (Marcel Duchamp/Collection Fabio Sargentini, Rome)

Negotiating those decisions is a matter of exploration and exploitation. As Christian & Griffiths (2016) explain in the popular science treatment *Algorithms to Live By,* 'exploration is gathering information, and exploitation is using the information you have to get a good result'. So when should one explore, and when exploit? The authors hold that a winning strategy would be to 'explore when you will have time to use the resulting knowledge, exploit when you're ready to cash in. The interval makes the strategy'. This recommendation is good advice. If there is ample computing time to simulate and analyse the out data for each and every design option (phenotype) using the exact parametric in data (for all objectives), then this exploration is likely to be worthwhile.

This is one of the reasons nature is such a successful designer: it has access to populations-based operations, coupled with a unique ability to negotiate the exploration-vs-exploitation trade-off. The evolutionary process features both operators: selection and breeding focuses primarily on exploitation, while mutation explores novel designs that contribute to the diversity of the species, ensuring its long-term survival by allowing it to adapt to a constantly changing environment. The procedure somehow resembles the famous door in Marcel Duchamp's Paris studio, at 11 rue Larrey, which curiously served two doorways: opening one door closed another (Figure 5). Decisions depend on prior decisions: exploiting a newly-discovered and promising strategy makes further exploration unattainable, despite such an exploration possibly yielding an ultimately better outcome.

To better understand this, let us return to our example of the maze above. At a fork, you make a decision, choose variable A, and turn left. But this might mean you no longer have access to any of the paths and corridors that were available to you had you chosen variable B, and turned right. Design processes are highly path dependent, with early decisions often determining and limiting the possibilities of later-stage designs. A critical decision might cut off the design space, severely limiting the possibilities to explore alternative options at a later stage. This is one of the reasons why any evolutionary optimisation process is unlikely to achieve a truly 'optimal' design (the very best phenotype within the entire design space).

It is also one of the reasons why a system such as AAA is best implemented at the earliest possible stage of the design process. Early design decisions have the greatest impact on a project's success or failure. In a probing PhD thesis, Davis (2013) shows how a graph that in 2004 became known as the MacLeamy curve (after HOK chairman Patrick MacLeamy) in fact originated in a 1976 paper by Stanford engineering professor Boyd Paulson, and concludes that 'the real benefit of learning to think parametrically comes from the cost of design changes'. The MacLeamy curve has become somewhat of a cliché, but a helpful one: it suggests that during the course of a project, the cost of making changes increases as the architect's ability to impact cost and functional capabilities of the design declines. AAA thus needs to be applicable to the early stage design process where it has the potential for the greatest impact on the overall building life cycle performance.

2.7 Species of spaces

In Frazer (1995), trailblazing architect John Frazer summarised three decades' worth of using nature's processes of evolution and morphogenesis as an analogy to create a novel theory of architecture as the design of thermodynamically open systems. (While an open thermodynamic system is able to exchange energy and/or matter with its surroundings, a closed, or isolated, system is completely separated from its surrounding environment; strictly speaking, unless the system is defined as the entire universe, truly closed systems do not exist in reality.)

In his prophetic book, *An Evolutionary Architecture,* and throughout the academic work that preceded and superseded it, Frazer treats architecture as a form of artificial life, operating like an organism. Attempting to evolve forms by emulating genetic processes found in nature, the architect suggested that evolutionary logics can be used to generate forms, or rather the operations that generate forms, as explained in Frazer (2002): ‘We are describing processes, not components; ours is the packet-of-seeds as opposed to the bag-of-bricks approach’.

If this sounds like science fiction, Paper I states that it is quite the opposite, and that the unrealistic attitude is rather a hallmark of romantically ‘uncompromising’ modernist ADs:

> As opposed to the black-and-white world of Ayn Rand’s famously stubborn architect protagonist, Howard Roark, the real world features gradients between good and evil, right and wrong. Transferred to architecture, this might mean several competing objectives are present in a building at once: spatial or geometrical ideas might be pitted against structural concerns, in turn fighting a battle with programmatic visions and the financial realities of the project. The result is always a compromise between the best (or least bad) alternatives given the circumstances. Unless Roark commissions himself to build every part of his buildings under factory conditions, he will not be the free soul Rand intended him to be.

To fully appreciate the avant-garde nature of Frazer’s idea of a packet of digital architecture seeds, and to finish setting the scene for the explorations of the AAA concept to follow, it might be judicious to briefly trace the outline of humanity’s part in the history of genetics, our analysis of evolution and morphogenesis, and the relatively recent invention of evolutionary computation, which inspired avant-garde architects to begin breeding buildings. This will be the topic of chapter 3.

BACKGROUND

3. BACKGROUND

What follows is a framework composed of fairly strong claims, and in a contribution of this length, the usual caveat is required as to the necessary brevity of the arguments supporting those assertions. While some of the ideas and theoretical constructs expounded may sound challenging or even implausible, every effort will be made to explain them as unambiguously as possible. Having said that, the exposition will introduce the fundamental ideas at the outset, then skip 'middle-range' elucidations that are already discussed in the literature to instead focus on their applications within the theoretical system of AAA. Readers interested in more detailed descriptions of theoretical minutiae are referred to the respective original sources; a short list featuring some of the most prominent ones can be found in chapter 11.

This chapter follows a trajectory from the moment of abiogenesis via human genetic understanding and engineering, the process of morphogenesis, through to evolutionary computation and its relevance to contemporary architecture practice.

3.1 The origin of life

Where to begin if not with abiogenesis, the origin-of-life processes by which life must have arisen from non-living matter? While the occurrence of abiogenesis is scientifically uncontroversial, its mechanisms are poorly understood. As noted in Fox (1988), the organisational evolution of biological structures are consequences of the flow of energy through matter, and as Witzany (2016) explains, today's prevailing scientific hypothesis for how pre-life chemical reactions gave rise to life is that several events combined to produce a gradual increase in complexity from molecular self-replication, via self-assembly and autocatalysis, through to the emergence of cell membranes. DeLanda (2011) is an elegant exposé of the 'prebiotic soup,' a hypothetical set of conditions present on Earth some 4.2 to 4.0 billions of years ago, in which this chemical evolution leading to the emergence of life is described in terms of 'gradients of concentrations of substances'. For supplementary readings on this 'heterotrophic' theory, see Oparin (1924) and Haldane (1929).

In a now-famous experiment published in the 15 May 1953 issue of Science, Stanley Miller (who Bada & Lazcano (2012) call 'the father of prebiotic chemistry'), together with Nobel laureate Harold Urey, used a gaseous mixture of methane (CH_4), ammonia (NH_3), and hydrogen (H_2) to simulate the ocean-atmospheric conditions of primitive Earth. As recounted in Miller (1953), they then exposed their 'soup' to electrical discharge, inducing a chemical reaction that, after a week, could be shown (using paper chromatography) to have produced amino acids including glycine, α-alanine, and β-alanine. This showed that natural organic synthesis could have made possible the origin of life on Earth.

Almost all known forms of life on Earth rely on the same set of rules, the genetic code of life, by which living cells translate information between their highly limited number of molecular building blocks. A mere 20 amino acids keep close to all terrestrial organisms alive. Guided by ribosomes (a macro-molecular machine within the cell responsible for protein biosynthesis) and carried by molecules known as transfer RNA (tRNA), those amino acids are linked together in a particular order specified by molecules called messenger RNA (mRNA). The mRNA is then 'read' by the tRNA one 'codon' (a long polymer composed of a triplet of organic molecules called nucleotides) at a time to produce proteins. According to the RNA world hypothesis described in Rich (1962), self-replicating RNA molecules came into existence before the advent of DNA and proteins. Renowned scientists such as Robert Shapiro and Francis Crick have opposed this, arguing that the complexity of life is too great to have arisen naturally on the primitive Earth, and opting that life arose, as suggested in Shapiro (1987), from the metabolism between simple molecules, or even, as argued in Crick (1981), as a result of 'seeding' by an extraterrestrial civilisation.

3.2 The code of life

As Gell-Mann (1994) suggests, natural evolution and the human development of the scientific method are essentially similar processes. Fusing these two themes together, the quest to understand genetic processes is a defining moment in human history. According to Brown et al. (2009), archaeological evidence points to selective breeding – the human intervention in the sexual reproduction of animals or plants to selectively develop particular characteristics (phenotypic traits) by choosing which males and females will have offspring – having been carried out as early as 13,000 years ago in some parts of South America, in the Yangtze region of southeast Asia, and in the Fertile Crescent (an alluvial plain between the Tigris and Euphrates rivers).

As Hillman et al. (2001) demonstrate, at the end of the last Ice Age, hunter-gatherers began domesticating rye and other cereal crops on the Euphrates. Soon after this early cereal cultivation, the breeding and herding of goats, sheep, and pigs were added to form a diverse agricultural economy, and a plethora of new breeds have, of course, been developed ever since. As shown by Martin & Hine (2004), the thousands of cultivars (cultivated varieties) of individual crop plants species in existence include, for instance, more than 4,000 different peas *(Pisum sativum)*, and 5,000 grapes *(Vitis),* adapted to different climates and soils.

According to Hartl & Jones (1998), these early farmers recognised that certain plant and animal features were passed from generation to generation, and that traits such as size, speed, and weight (in animals) or crop yield and climate resistance (in plants) could be controlled by strategic mating or cross-pollination. This method of crossbreeding for desirable traits had thus been known for millennia when scientist and Augustinian friar Gregor Mendel conducted his famous pea plant experiments between 1856 and 1863. Three years later, Mendel's rules of heredity, today known as the laws of Mendelian inheritance, were published in the seminal Mendel (1866) paper, which would eventually go on to forever change the study of biological inheritance.

The ideas were indubitably in the air. The 1850s and 1860s are decades that mark the golden era of evolutionary theories, years in which Alfred Russel Wallace anticipated Charles Darwin's theory of evolution by natural selection with the publication of Wallace (1855); Darwin and Wallace jointly presented their ideas to the Linnaean Society of London (in 1858); Darwin (1859) published *On the Origin of Species by Means of Natural Selection;* Rudolf Virchow (1859) finalised the cell theory by declaring cells to be the basic units of all living things; German zoologist Ernst Haeckel (1866) incorporated the principles of Darwinian evolution in his *General Morphology of Organisms,* the first detailed genealogical tree relating all known organisms; Thomas Henry Huxley (1868) argued that birds are descendants of dinosaurs in the beautifully titled article *On the Animals which are Most Nearly Intermediate between Birds and Reptiles* (a theory that was not taken seriously for another century); and Francis Galton (1869) concluded that human intelligence has a genetic basis. And then there was Mendel and his garden of peas.

Mendel's idea of heredity units (hereditary 'factors' in Mendelian parlance) is today known as *genes*, and the scientific study of heredity is called *genetics*. But as Bowler (2003) points out, it took more than three decades for the profound significance of Mendel's work to be recognised. It wasn't until the year 1900, when three botanists – Hugo de Vries in the Netherlands, Carl Correns in Germany, and Erich von Tschermak in Austria – independently rediscovered Mendel's writings that his experiments gained renown. Indeed, the word 'genetics' was only coined in 1906, by 'one of the major Mendelians in the world,' biologist William Bateson, to designate what Gayon (2016) calls 'the science of heredity and variation'. Mendel's laws are explicitly connected with the general question of heredity in Bateson (1902), a zoomed-out perspective entitled *Mendel's Principles of Heredity: A Defence*.

It was around this time that geneticists started to reflect on the topic of molecular genetics, probing into questions of genetic anatomy and data. Was the gene a molecule? How was genetic information encoded and transmitted from one generation to the next? How did this genetic information change in mutant organisms? It would take several decades to find the answers: Hartl & Jones (1998) note that it wasn't until the 1940s that the molecule deoxyribonucleic acid (DNA, first isolated by Friedrich Miescher in 1869) was implicated, and that it would take another decade before Watson & Crick (1953) reported that the double helix structure of that DNA molecule, constructed from nucleotides, had been discovered by James Watson and Francis Crick (and Rosalind Franklin, though being female her contributions to the discovery were largely recognised posthumously).

Three exciting decades followed, during which the scientific world came to an understanding not only of the chemical nature of genes, but of how the genetic information is stored, how it gets released to a cell, and how it is transmitted from one generation to the next, building up a body of genetic knowledge that, in the words of Hartl & Jones (1998) 'grew with a two-year doubling time'. Of particular importance were two events of 1961: 1) the first model of regulation of gene expression (the lactose operon model) by François Jacob and Jacques Monod (Jacob & Monod 1961), and 2) the cracking of the genetic code by Francis Crick, Sydney Brenner, Leslie Barnett, and Richard Watts-Tobin, the 'code of life' – an algorithm that connects 64 RNA triplets to 20 amino acids, and that has been called 'the Rosetta stone of molecular biology' (Crick et al. 1961). Anecdotally, Tamura (2016) tells us that Francis Crick produced the world's first written description of the genetic mechanism, the 'fundamental principle of biology,' in a letter to his 12-year-old son, Michael.

3.3 Genetic engineering and morphogenesis

But mapping the code of life of course wasn't the end of the history of genetics. From the early 1970s onwards, an impressive list of discoveries has been added to our toolbox of 'genetic engineering,' methods that, to quote Hartl & Jones (1998), 'enable genes to be transferred, at the will of the molecular geneticist, from one organism to another'. The discovery of split genes, alternative splicing, non-universality of the genetic code, and noncoding ribonucleic acid (RNA – as Gayon (2016) explains, 98.5% of our genome is not translated into proteins, but more than 70% is transcribed into RNA). In the 1980s, the focus shifted again to emphasise genomics, with geneticists applying recombinant DNA strategies to study entire genomes (all of an organism's genetic information) rather than single genes.

While these genetic studies demonstrated a physical mechanism for inheritance, their insistent focus on biochemical processes to some extent pushed aside another important topic: morphogenesis, what Bourgine & Lesne (2011) call the 'ensemble of mechanisms underlying the reproducible formation of patterns and structures and controlling their shape'. Derived from the Greek *morphê* (shape) and *genesis* (creation), morphogenesis, along with the control of cell growth and cellular differentiation, is one of three fundamental aspects of evolutionary developmental biology ('evo-devo'). According to Bourgine and Lesne, morphogenetic studies seek to understand 'the causes of the shapes we observe,' that is, elucidate how biological growth is affected by physical processes and constraints, giving rise to natural patterns and forms. This biological growth includes the organisms' ontogeny (development of organs, systems, and parts) as well as their evolutionary development (phylogeny). As noted in Waddington (1956), in the strict sense, the word should mean 'the molding of cells and tissues into definite shapes,' though more often than not, 'morphogenesis' is used to refer to many aspects of development, including non-biological ones.

Building on this and later research, digital morphogenesis, also known as morphogenetic design, is a concept originally developed in biology, and later applied to an extended field that includes geology, geomorphology, art, and architecture. A collection of tools and methods that allow an AD to create forms that can be adapted to their environments, digital morphogenesis is, as Roudavski (2009) explains, similar to its biological counterpart in that its development is gradual, without an explicit definition of the methods of growth or adaptation. Kolarevic (2000) describes digital morphogenesis as 'computationally based processes of form origination and transformations,' while Leach (2009) states that it refers to

> the logic of form generation and pattern-making in an organism through processes of growth and differentiation. More recently it has been appropriated within architectural circles to designate an approach to design that seeks to challenge the hegemony of top-down processes of form-making, and replace it with a bottom-up logic of form-finding. The emphasis is therefore on material performance over appearance, and on processes over representation.

Correlating morphogenesis with ecology, the *Morpho-Ecologies* volume by Hensel & Menges (2006) is a noteworthy collection of early theories, experiments, and projects within the rapidly accelerating field of morphogenetic architecture.

3.4 Conflict and compromise: Evolutionary computation

In tandem with the 'wet' engineering of genes and enlightening studies of biochemical and morphogenetic processes outlined above, a parallel effort aimed at translating the inner workings of evolution to an *in silico* environment was underway. A helpful historical review of early attempts to generate machine learning through simulated evolution can be found in

Bäck et al. (1997), which together with De Jong et al. (1997) provides a good overview up until the late 1990s. Around this time, a veritable explosion of evolutionary computation occurred, which makes the development harder to track. In Fogel (2006), the author notes that in the ten years that had passed since the first publication of that book

> evolutionary computation has matured from a fringe element of computer science to a well-recognized serious endeavor. Although specific numbers are difficult to estimate, it would not be unreasonable to believe that over 10,000 papers have now been published in evolutionary computation.

The turn of the millennium was arguably the first renaissance for this nature-inspired branch of machine intelligence. While the term evolutionary computation was coined in 1991 (the first issue of a journal by the same name was published in 1993 by the MIT Press), its origins can be traced as far back as the late 1950s, when foundational work was carried out by pioneers such as Richard M. Friedberg (who worked on 'automatic programming,' the task of finding a program that calculates a given input-output function), Hans-Joachim Bremermann (who applied simulated evolution to numerical optimisation problems and developed some of the early evolutionary algorithm theories), and George E. P. Box (who advanced ideas about 'evolutionary operations' that involved an evolutionary technique for the design and analysis of industrial experiments).

These early studies were met with considerable skepticism from a conservative academia. Despite this, they initiated the development of the three main forms of evolutionary algorithms, which were clearly established by the mid-1960s. Described in Fogel et al. (1966), *Evolutionary Programming* (EP) was developed by Lawrence Fogel in San Diego, California. (Fogel's PhD thesis *On the Organization of Intellect* has been singled out as a tipping point that sparked the first endeavours into evolutionary computing; see Rutten (2011) and Fogel (1964), as well as Paper I). As recounted in Schwefel (1995), *Evolution Strategies* (ESs) were jointly developed by three students in Berlin: Ingo Rechenberg, Hans-Paul Schwefel, and Peter Bienert. And as recalled in Holland (1975), *Genetic Algorithms* (GAs) were developed by John Holland at the University of Michigan in Ann Arbor. Over the next 25 years each of these branches developed quite independently of the others. However, the lack of powerful computer platforms meant the field didn't really make any noise until the 1970s.

The narrative is expertly summarised in De Jong (2006). Fogel's work on EP from 1960 onwards centred on the connections between intelligence and anticipation, and how such connections can be used to simulate evolution using finite-state machines (a mathematical model of computation). As De Jong et al. (1997) write:

> Fogel considered intelligence to be based on adapting behavior to meet goals in a range of environments. […] Intelligent behavior was viewed as requiring the composite ability to (i) predict one's environment, coupled with (ii) a translation of the predictions into a suitable response in light of the given goal.

In the beginning, Fogel successfully applied EP to problems in prediction, identification, and automatic control. Additional experiments evolving finite-state machines for sequence prediction, pattern recognition, and gaming ensued between 1969 and 1980. In the mid-1980s, Fogel extended the procedure to tackle the travelling salesman problem, continuous function optimisations, route planning, optimal subset selection, and the training of neural networks. In the 1990s, EP was applied to a wide range of fields including robotics, path planning, neural network design, and automatic control.

ESs were invented as an improvised side product during the creation of a research robot that were to perform series of experiments on a flexible slender three-dimensional body in a wind tunnel so as to minimise its drag. Primarily used to explore the use of evolutionary models in the design of efficient experimental optimisation techniques, ESs are the least developed of the three main forms of algorithms used in evolutionary computing. GAs, on the other hand, are the most successful application to date, commonly used to generate high-quality solutions to optimisation and search problems, including multi-objective optimisation (MOO) challenges, and certainly the most-used implementation of evolutionary computing in the fields of architecture and engineering today. To understand why this is, we need to appreciate the nature of MOOs.

As we saw in the above discussion of design space dimensionality, the process of designing something is per definition not only a decision-making process, but an inherently *multidimensional* operation. Decision making itself was defined by Hwang & Masud (1979) as 'the process of selecting a possible course of action from all the available alternatives'. In most situations, and undoubtedly throughout the decision making that defines a design process, 'the multiplicity of criteria for judging the alternatives is pervasive,' that is, the decision maker 'wants to attain more than one objective or goal in selecting the course of action while satisfying the constraints dictated by environment, processes, and resources'. MOO is a technique used within the field of multiple-criteria decision making as a response to such situations.

In the interest of clarity, it should be noted that a MOO typically isn't capable of providing a single solution that simultaneously optimises for all objectives, but rather a (possibly infinite) number of compromises between conflicting objective functions. These are called Pareto optimal solutions, and are considered, as noted by Ehrgott (2005), equally good until a subjective preference (such as the designer's desires, or a list of preconceived targets) is added to the system.

As Ahn (2006) points out, the reason that the stochastic, population-based search and optimisation algorithms we know as GAs work so well for engineering optimisations is that, inspired by the process of natural selection and genetics, they

> work with a population, unlike other classical approaches which operate on a single solution at a time. Hence, they can explore different regions of the solution space (i.e., search space) concurrently, thereby exhibiting enhanced performance.

Furthermore, Ahn explains, GAs are 'powerful search mechanisms' that 'traverse the solution space in search of optimal solutions'.

John Holland invented GAs as part of his ambitious broader agenda to understand the underlying principles of complex adaptive systems (capable of self-modification in response to interactions with the environments in which they function; we shall return to these in the Discussion), which culminated with the book *Adaptation in Natural and Artificial Systems* (Holland 1975). GAs were designed to support both the exploration of natural adaptive systems and the design of robust adaptive artefacts. As De Jong et al. (1997) report:

> In Holland's view the key feature of robust natural adaptive systems was the successful use of competition and innovation to provide the ability to dynamically respond to unanticipated events and changing environments. Simple models of biological evolution were seen to capture these ideas nicely via notions of survival of the fittest and the continuous production of new offspring.

It was with the work of Holland and his PhD students that the lingo of evolutionary computation got its distinct genetic flavour, as solutions (assemblages) were represented internally as 'genomes' and references to other genetics operators such as mutation, crossover, and inversion abounded. The late 1960s and early 1970s were a golden era for GA studies, during which several important theses were published, including Bagley (1967), Rosenberg (1967), Cavicchio (1970), Hollstien (1971), Frantz (1972), and De Jong (1975). Simultaneously, Holland developed his *schema analysis* of adaptive systems, while also engaging in a more theoretical analysis of his *reproductive plans* (essentially simple GAs). From the mid-1970s onwards, the family tree of GAs branched out as other universities and research laboratories established research activities in this area. *Genetic Algorithms in Search, Optimization and Machine Learning,* a book by Goldberg (1989), was a particularly important publication that introduced GA theory to a broad audience of scientists and engineers.

Interestingly, many of the desirable properties of GA that were theoretically identified by Holland and his students could frequently not be experimentally observed. This is explained by De Jong et al. (1997) as, again, a matter of computational power:

> Hampered by a lack of computational resources and analysis tools, most of the early experimental studies involved a relatively small number of runs using small population sizes (generally less than 20). It became increasingly clear that many of the observed deviations from expected behavior could be traced to the well-known phenomenon in population genetics of genetic drift, the loss of genetic diversity due to the stochastic aspects of selection, reproduction, and the like in small populations.

Indeed, this illustration of GAs as computationally intensive procedures still applies. In an elucidating blog post, Rutten (2011) discusses how evolutionary principles can be applied to problem solving using GA and the Galapagos evolutionary solver. Setting out to highlight 'some of the (dis)advantages of this particular type of solver,' his first point is to do with computational strain:

> Evolutionary Algorithms are **slow**. Dead slow. It is not unheard of that a single process may run for days or even weeks. Especially complicated set-ups that require a long time in order to solve a single iteration will quickly run out of hand. A light/shadow or acoustic computation for example may easily take a minute per iteration. If we assume we'll need at least 50 generations of 50 individuals each (which is almost

> certainly an underestimate unless the problem has a very obvious solution.) we're already looking at a two-day runtime.

It should be noted that without creative tweaking, Galapagos does not cater to multi-objective optimisation problems, which typically take considerably longer to solve. Rutten's language and examples are very easy to understand, and the Galapagos evolutionary solver plug-in that he introduces, developed for the Grasshopper environment that Rutten himself created, can be viewed as the decisive turning point for the use of evolutionary algorithms as an architectural form-finding strategy.

This is nothing if not highly commendable, but in effect, everything Rutten discusses in that post was already covered by Luisa Caldas in her prescient PhD thesis, published ten years earlier, at a time when the use of GAs in architecture was a substantially more involved procedure than it is today. Caldas (2001) introduced in a coherent manner and using exceptionally clear implementation examples a strategy by which the collected knowledge from previous researchers working in a wide range of neighbouring fields (from mathematics to engineering) might be used to form what is for all intents and purposes an entirely new genre within architecture: the environmentally-driven genetic paradigm. Specifically, Caldas studied an evolution-based generative design system that used adaptation (to climate simulations) to shape architectural form and generate an optimal fenestration. Making an inspired leap of abstraction, Caldas turned the building into a chromosome:

> If a building can be fully described using a 3D CAD model and text [like materials specifications], there is theoretically no reason why it cannot be fully described by a single string of symbols [numbers, mathematical operations and words], what in a GA environment would represent a chromosome [and having established such a computer-generated chromosome representation of a building] departing from initial rules and abstract relationships, and by manipulating data structures, any potential architectural shape can emerge, depending on the initial rules and the flexibility of the CAD platform used to encode any type of geometry.

In contemporary architecture practice, having structures accomplish satisfactory building performance as well as efficient and sustainable levels of operational and embodied energy are arguably a mandatory requirement. AAA's way of achieving this is to feed life cycle assessment (LCA) values, energy simulations, and related data to multi-objective optimisations of real-time parametric digital models controlled by GA-based evolutionary solvers. While an extensive review of the literature within this field is beyond the scope of this paper, brief remarks will be made on a few texts to contextualise the current enquiry. A helpful and reasonably recent review of papers on architectural design optimisations for energy efficiency can be found in Shi et al. (2016).

Wilson & Templeman (1976) described a computer-based model for determining the thermal design of an office building with minimum initial and operating costs, using the total discounted cost of the entire heating and insulation process as their optimality criterion. D'Cruz et al. (1983) is another very early paper on mathematical building optimisation 'for the classic building design problem of choosing a building form, enclosure and siting given several different and conflicting performance requirements'. Al-Homoud (1994) describes the energy-conserving optimisation of building envelopes. Referencing the already-mentioned work by Caldas, Wright & Mourshed (2009) found that a more dynamic fenestration optimisation experiment that utilised genetic algorithms to optimise each cell of a cellular façade was an effective way of minimising (operational) building energy use while allowing for innovative and interesting architectural forms. Similar ideas are explored in Paper III and Paper V.

Thoroughness is also a theme in Al-Homoud (2005), which describes a building energy simulation system that estimates the annual energy performance of buildings, including daylighting, demand charges, life cycle costs, and floating temperatures in unconditioned zones, while also offering an historical account of the field. This is an early example of life cycle aspects being used for building optimisation purposes. Examples of explicitly LCA-based papers aimed at using computation to reduce life cycle costs, material costs, energy consumption, and environmental impact include Wang et al. (2005), Hasan et al. (2008), Palonen et al. (2009), Fesanghary et al. (2012), Yuan et al. (2012), Ihm & Krarti (2013), Karaguzel et al. (2014), Carreras et al. (2015), Junghans & Darde (2015), and Hollberg & Ruth (2016).

Bringing the discussion even closer to home, Otovic et al. (2016) discusses the concept of Integrated Energy Design (IED) – where net-zero-energy architecture is achieved by intelligent decision making during the earliest stages of a design, when factors such as building geometry, orientation, and façade design are determined – and the development of 'a real-time LCA simulation tool' based on Grasshopper and the Honeybee plug-in.

ONTOLOGY

4. ONTOLOGY

Why do architects and engineers need an ontology? Because such a philosophical examination of being (and becoming, and existence, and reality) productively frames (constructively constrains) our view of the world, anchors our understanding of its mechanisms, and defines ways in which we may interact with it. Our diagrammatic model of how reality comes into being and maintains its existence influences our anticipation of how we, as designers and researchers, may be able to interrogate and sculpt the world around us. As Zio (2013) notes, when designing a new system

> or attempting to improve an existing one, the engineer tries to anticipate future patterns of system operation under varying options. Inevitably, the prediction is done with a model of reality, which by definition can never fit reality in all details. The model is based on the available information on the interactions among the components of the system, the interaction of the system with the environment, and data related to the properties of the system components. All these aspects concur in determining how the components move among their possible states and, thus, how the system behaves. With the model, questions can be asked about the future of the system, for example in terms of its failures, spare parts, repair teams, inspections, maintenance, production and anything else that is of interest.

To this notion of the *anticipation* of a system's *adaptation* (its assumed or projected 'operation under varying options'), which yields an *ontology* (a 'model of reality') that in turn produces a design *methodology* (a collection of ways to influence the behaviour of the system) that includes an *epistemology* (providing the possibility of gaining knowledge by asking questions 'about the future of the system') can be added an *axiology* – the value-based reasons for designing the system and introducing difference in the first place. But this expanding theoretical understanding arguably requires the foundational existence of an ontology, premised on a basic theory of fundamental causal mechanisms, parts of which have typically already been constructed by previous thinkers. Since this part of the thesis constitutes the fundamental premise upon which the rest of the argumentation rests, it will be considerably longer than the ensuing chapters.

An ontology is defined as the set of entities that a particular philosophical theory asserts actually exists, the types of entities that this philosophy assumes populate reality. It should be noted here that the AAA ontology makes no claim of being exhaustive: it is only concerned with those ontological aspects that are of use to ADs in the design of AAAs and PETs. Ontological positions can be broadly divided into three groups: 1) idealism, which anthropocentrically holds that reality does not exist independently of the perceiving human mind, 2) pragmatism/positivism/instrumentalism, which hold that while objects of everyday experience are mind independent, theoretical entities (unobservable relations and entities) are not, and 3) realism, which holds that reality is fully autonomous from the human mind. Deleuze, DeLanda, and AAA are proponents of realism.

What entities exist in this mind-independent world? If we are to believe Deleuze, roughly three things: multiplicities and assemblages (which perhaps essentially amount to the same thing, so that in fact we may only be left with two entities), produced by difference. In

DeLanda (2002b), we learn that the concept of multiplicity 'stands out for its longevity' in Deleuzian thought. This notoriously elusive term is specified in Deleuze & Guattari (1991) as 'substance itself,' as well as a 'difference' that specifies the 'structure of spaces of possibilities,' which explain the regularities present in morphogenetic processes. Protevi (2011) shows that Deleuze's formula for how the world works can be reduced to the following three steps:

> (1) intensive morphogenetic processes follow the structures inherent in (2) virtual differential multiplicities to produce (3) actual localised and individuated substances with extensive properties and differentiated qualities.

Abridged even further: actual entities (including, for instance, buildings) in the world result from intensive processes that actualise virtualities. Let us take apart this formula, study its parts in the light of DeLanda's helpful analyses, and then piece them back together again in a slightly different way to produce our AAA ontology.

The chapter is structured as follows: the contemporary philosophical field that DeLanda is an instrumental part of, new materialism, is presented. The idea of multiplicities is introduced, together with an argument aimed at eliminating the ideas of (philosophical) essences and (architectural) types. A section on interior and exterior relationships seeks to similarly obliterate the organism metaphor, before the discussion turns to the mechanisms of multiplicities (which give birth to space) and assemblages (which maintain space) that define AAAs. The Deleuzean notion of double articulation is used to explain how those AAA mechanisms are interrelated and organised, before the final AAA ontology is summarised.

4.1 New materialism

The ontology presented here owes a major debt to the relatively nascent field of new materialism, a school of thought described in DeLanda (2015) as 'an entirely new conception of the material world'. This conception in DeLanda's view encompasses a series of redefinitions of and/or improvements to older concepts, including notions of causality (expanded to include not only linear but also nonlinear patterns, while also allowing for different causes to yield the same effect or the same cause to yield different effects), the characterisation of material systems by their (virtual and real but not always actual) capacities as well as their (always actual) properties, and the conception of the virtual as having a structure 'formed by differential elements and distributions of singularities'. The main proponents of new materialism include Rosi Braidotti, Manuel DeLanda, Jane Bennett, and Karen Barad. The movement is at times bundled with neighbouring theories proposed by philosophers such as Bruno Latour (ANT) and Graham Harman (OOO), sometimes under the term 'speculative realism' (a term originally proposed by Quentin Meillassoux).

Out of these, autodidactic philosopher Manuel DeLanda is the new materialist thinker that has arguably had the greatest impact on the design professions. As Lemke (2015) explains, DeLanda's point of departure is the idea that 'all objective entities are products of a particular historical process: a cosmological, geological, biological or social history'. This leads to what Van der Tuin & Dolphijn (2010) view as a 'series of movements exploring a monist perspective of the human being' that offers a new reading of the monist tradition, a philosophical trajectory that can be visualised as a timeline populated by thinkers such as Lucretius, Duns Scotus, Spinoza, Hume, Nietzsche, Whitehead, Bergson, and Deleuze (at times together with Guattari).

Furthermore, DeLanda's theories frame a philosophy that according to Choat (2017) has been defined by reference to three specific criteria: 'a reappraisal of science; an emphasis on the agency of all things; and, underpinning all this, a "flat" ontology'. An attempt at summing up its message might read: matter is vibrant, everything has agency, and while entities have different capacities to produce effects, none of them is any more real than any other. In DeLanda (2017), the philosopher himself outlines his research project thus:

> Old forms of materialism are either obsolete (Dialectical Materialism) or are reductive (all material entities are just clouds of subatomic particles). Neo-materialism attempts to replace Dialectics with a new concept of synthesis (based on the concept of self-organization) and to block reductionism via the concept of emergence.

This new school of thought is not without its critics – in particular, unsurprisingly, from the dialectical materialist camp: critical theorist Benjamin Noys (2016) accuses the new materialists of positing matter against materialism, while continental philosopher Slavoj Žižek (2014) describes its views as being 'materialist in the sense in which Tolkien's Middle-earth is materialist,' a judgement that (Marxist) theorist Terry Eagleton (2016) alludes to in his review of new materialism, which he describes as 'essentially a pagan vision,' before launching a particularly venomous critique against (the outspokenly anti-Marxist) movement, which he refers to as 'a strangely immaterial brand of materialism' that lends matter a 'pseudo-metaphysical status'.

Be that as it may, following an appraisal of the projects that have come out of architecture schools in the past two decades or so, no critic would be able to deny DeLanda's impact on a certain brand of philosophically-minded students, a fact brought home by SCI-Arc philosophy professor Graham Harman, who in Harman (2016a) opted that DeLanda 'has been largely ignored by professors of philosophy but adored by graduate students – a demographic profile that usually indicates a thinker of high calibre, a full generation ahead of peers'. Without doubt, DeLanda and his followers have been highly influential in reshaping the way ADs think about matter, materials, and material flows.

It is presumed here that the endeavour of designing structures for the world we inhabit is based on the act of thinking logically, critically and holistically about that same world. This is not a given: plenty of designers – at the scale discussed here, architects and engineers – go about their work without considering the processes that underpin the fabric of everyday existence, but this ignorance of course makes it quite impossible to tap into, harness, and constructively utilise as parts of a design process theories about how the world might work.

We just called new materialism a 'relatively nascent field,' but it is based on a long tradition of more or less realist thinkers that includes Foucault, Bergson, Whitehead, Hume, Spinoza, and more. For the present discussion, however, we need not consider that entire genealogy, but can limit ourselves to the discourse developed by DeLanda following what Harman

(2016a) calls an 'astonishing period of self-education in philosophy,' which led not only to his first book being published in 1991, but in particular to DeLanda beginning his creative readings of Gilles Deleuze.

It was DeLanda's 'reconstructions' of Deleuze's concepts that five years later, in DeLanda (1996), led him to introduce the term 'neo-materialist' as a way to conceptualise the structure-generating processes underlying geological formations (and other 'strata' and 'meshworks') as a result of the reasoning in Deleuze & Guattari (1980) on 'abstract machines' and 'double articulations'. We shall return to these ideas shortly. Two important connections can immediately be made between DeLanda's paper and the present thesis: 1) its focus on genetic processes ('genetic materials "sediment" just as pebbles do,' writes DeLanda), and 2) his description of the abstract machine as an 'engineering diagram' that is 'shared by very different physical assemblages,' exemplified by the way in which a hurricane and a steam engine use the same principle 'with different physical instantiations in technological objects and natural atmospheric processes'. A plethora of such connections exist, as will soon become clear.

DeLanda's reading of Deleuze is creative – as the author notes in DeLanda (2009), the 'best way of honoring (Deleuze's) memory is not to stick to what he said in every detail but to push the line of flight that he rode in his life and work to its ultimate consequences'. Pushing this line of flight to *its* ultimate consequence, AAA does not stick to what DeLanda says in every detail. The present reading of DeLanda reading Deleuze is thus a reconstruction of a reconstruction, a commentary on the commentary.

By adding to DeLanda's assemblage scheme the mechanisms of anticipation and adaptation, by extending and developing further Deleuze's critique of hylomorphism, by positioning such a view of the world vis-á-vis both architectural theory and design practice, and in later chapters by making explicit some of the connections between this ontology and an architectural methodology as well as a design-oriented epistemology and axiology, this thesis thus reconstructs DeLanda's reconstruction of Deleuze into AAA, a realist and materialist theory of design.

4.2 Beyond essences and types: Populationist manifolds

DeLanda's creative reading of Deleuze has no room for the philosophical concept of essences (Deleuze himself was not quite as adamant, as Kleinherenbrink (2019) shows). This position of DeLanda has a particular bearing when applied to the field of architecture, which has a long history of theories on typologies. AAA joins DeLanda in abolishing essences and types from its ontology. Let us attempt to explicate this by introducing Deleuzean multiplicities.

By way of its architectural *morphogenesis* – the origin and development of architectural form – every project by definition emerges from a *multiplicity*. It is always quite possible to conjure up variations on any given architectural theme or engineering scheme, to envisage minute or radical alterations to a geometry or a concept. New performance requirements may be introduced, various constraints imposed or relaxed, an alternative façade material or structural system proposed. Attractors might shift into repellers, budgets get altered, or the entire project may suddenly be moved to an alternative site that presents new possibilities and difficulties: as Dylan (1974) reminds us, a change in the weather is known to be extreme.

Deleuze (1986) describes how the notion of a 'multiplicity' started in the field of physics and mathematics with the distinction between discrete and continuous manifolds offered by Riemann (1868), and was originally further developed as a philosophical concept in Bergson (1889) and (of lesser importance to Deleuze) Husserl (1929). Neither the highly technical formal definition of the term nor the accompanying historical account of its invention are crucial to the present argument; the former is presented in Deleuze (1966), and for a rigorous exposition of the role of Riemann in Deleuze's reading of Bergson, interested readers may consult Widder (2019). Here, it may suffice to note that this specific concept forms an important part of Deleuze's philosophy in general, and that it is of particular significance to his collaborations with Félix Guattari. We may also note that in Deleuze (1986), the philosopher points out that 'the most decisive step yet taken in the theory-practice of multiplicities' is to be found in Foucault (1969).

If we accept this idea of the architectural project as a multiplicity, that is, if we acknowledge the possibility of potential *alternative* versions that the architectural project might have turned into had it not become the present one, then it follows that the genesis of an architectural geometry is somehow based on a *dynamic* process. Hensel et al. (2006) define 'morphogenetic' architectural structures as 'complex energy and material systems that have a lifespan, exist as part of the environment of other active systems, and as an iteration of a series that proceeds by evolutionary development'. This is approximately the kind of process we have in mind: the production of a AAA is a process that subjects a design system to contextual pressures and has it respond to those circumstances during its evolutionary genesis and throughout its ensuing maintenance.

We can think of such a process as a series of bifurcations; viewed in this way, the conception of a project can be compared to a path through a space of possible solutions, a long and winding road that forks at crucial decision points. Different combinations of decisions yield different designs. The work of architecture can thus be the form modelled before you, or – if some aspect was changed at any point during its conception (including a change in the process environment) – a slightly different form. Such dynamic processes have an *abstract* (or *virtual)* structure: if we record the development to document the outcome of the entire set of possible forms given the project's unique contexts and constraints, and one of the generated forms is later constructed as a physical building, then we will have produced a three-level mapping of the abstract structure that gave birth to it. The resulting map will feature 1) the set of virtual (and real) forms composing the entire design space, 2) the set of virtual (and real) forms explored by the AAA, and 3) the final, *actualised*, and thus obviously real, form. Using the term 'machine' to denote the elementary units of being (as Deleuze and Guattari do), Bryant (2014) proposes that such a 'mapping of interactions and relations between machines composing assemblages or ecologies' be called a 'cartography'.

A cartographer can map two kinds of spaces, one exhibiting properties to do with space and movement (such as length, area, and volume) that added to each other yield only a *quantitative* change, the other exhibiting properties to do with time and speed (such as temperature, pressure, concentration, and voltage) in which addition can result in a *qualitative* change. The former is called *extensive* space, the latter *intensive* space. AAA allows intensive properties to generate qualitatively different states for a geometry as it reacts and adapts to the combined intensive-extensive space of the multiplicity from which it is made. The AAA cartographer maps the (extensive and intensive) space of the multiplicity by exposing the assemblage to morphogenetic processes and documenting the outcome. The same event simultaneously produces the map and constructs the AAA.

Why should ADs engage in such cartographic exercises? What is the use of this multiplicity? It replaces the much older philosophical concept of an *essence,* which can be found in Plato but originates rigorously with a precise and clear analogy presented in Book IV of Aristotle's *Politics*. DeLanda (2002b) describes essences as 'a core set of properties that defines what these objects are,' and goes on to declare that within a realist theory, 'one does not get rid of essences until one replaces them with something else'. This is because essences are defined as that which is necessary to exist: without an essence, the entity looses its very identity. The essential is contrasted with the *accidental,* properties that the entity might have contingently, while still retaining its identity. The essence of a thing thus explains its identity, and an ontology without identities is hardly possible.

But what is wrong with essences? Why not follow Aristotle – arguably for 2500 years or so the world's most influential realist thinker – and bundle together the fundamental traits that make an object what it is, then call these traits a 'common essence' when shared by many objects that could form a 'natural kind,' that is, a *species?* Because, argues Deleuze, such a set of defining characteristics that represent timeless categories disregards the fact that a species is an historically constituted entity that should not be defined by some 'essential traits,' but by the morphogenetic processes that gave rise to it. In other words, how something came to be is more important than what it resembles. DeLanda (2002b) explains that there are two reasons why this is a preferable model: 1) as opposed to the basically static essentialist explanation, the morphogenetic alternative is inherently *dynamic,* and 2) while the essentialist account

> may rely on factors that transcend the realm of matter and energy (eternal archetypes, for instance), a morphogenetic account gets rid of all *transcendent* factors using exclusively form-generating resources which are *immanent* to the material world.

We shall return to the importance of immanence in Deleuze's ontology in section 7.2 below, but it seems prudent at this point to first discuss the architectural idea of typology, which is closely related to essentialist thinking. The philosophical distinction between the essentialist and the morphogenetic model above is mirrored in digital architecture by a move away from type-based thinking towards a population-based approach.

Vidler (1976) suggests that typological thinking in architecture can be sorted into three distinct phases: thinkers such as Marc-Antoine Laugier and Antoine-Chrysostome Quatremère de Quincy in the 18th and early 19th century, who focused on nature and the primitive hut, belong to the first; industrialism and machine metaphors populate the second, the chief proponent of which is Le Corbusier; the city, particularly as investigated by Aldo

Rossi, makes up the third. As Wallenstein (2009) argues, in the writings of Quatremère, 'architectural form became its own model, an engendering of types whose basis lay in reason itself'. Reason yes, but a flawed reasoning indeed. In Quatremère's typological thought an object is an applied 'type,' and every architectural design the application of such a type, or essence. However, as Wallenstein goes on to note, there is a silver lining to this wretched state of affairs: 'To the extent that the theoretical and the practically oriented projects that we find in Ledoux, Boullée, and Quatremère look back to the authority of antiquity, they must fail; but in opening up the path toward a generative architecture they succeed, partly against their own will, and in a way that changes the terms of the problem itself'.

Trummer (2011) shows that many relatively recent avant-garde attempts at using computer-aided design to produce new forms of variation in architecture were still based on such an essentialist, typological thinking, based on another Aristotelian concept: *hylomorphism.* Writes Trummer: 'when we design a table by means of the hylomorphic model, we take a form (morph) – the image of the table we would like to design – and press it into the wood (hyle) – the material by which the image should be realised'. The real potential of computational techniques, argues Trummer, 'is to overcome any idea of typological thinking and to come up with a thesis of a design practice based on morphogenetic processes (that) require an understanding of the architectural object as population rather than as a type'. To this we may add: and an understanding of that object's materiality, in terms of its non-hylomorphic tendencies and capacities, as a possible morphogenetic constraint. Today's fabrication technologies allow materials to be moulded into almost anything. This may be a valid approach, but an alternative (and often better) strategy is to constrain the geometries according to their individual materiality-based form-giving capacities.

DeLanda (2002b) explains the nature of Deleuze's multiplicity by way of a related term borrowed from differential geometry: *manifold.* Studying curved two-dimensional surfaces in the early 19th century, German mathematician Friedrich Gauss 'developed a method to implant the coordinate axes on the surface itself,' as opposed to embed it within a three-dimensional space carrying its own set of axes. Gauss's compatriot Bernhard Riemann developed this technique further by defining N-dimensional surfaces exclusively through their intrinsic features. These latter surfaces were referred to as 'manifolds,' and as DeLanda points out, Deleuze's multiplicity 'takes as its first defining feature these two traits of a manifold: its variable number of dimensions and, more importantly, the absence of a supplementary (higher) dimension imposing an extrinsic coordinatization, and hence, *an extrinsically defined unity'*. This differs from essences, which do possess a defining unity and 'are taken to exist in a transcendent space which serves as a container for them or in which they are embedded'.

We can begin to explain how multiplicities (as opposed to essences) relate to the physical processes that generate entities in the world by pointing to a particular relation between the geometric properties of manifolds and the properties that define morphogenetic processes. In dynamical systems theory, a particular process or system is mapped using the dimensions of a manifold, which show how large the space of the system's possible states is. Nagy (2017) uses a striking image of birds to explain this dimensionality. While the birds' physical bodies occupy three dimensions, their circumstances act as dimensional constraints: the first bird, sitting on a pole, cannot move, and thus occupies a 0-dimensional space. A bird balancing on a telephone cable can only move along a single axis (that of the cable), and so occupies a 1-dimensional space. A bird on the ground can move in two spatial dimensions, occupying a 2-dimensional space. Only a bird in flight occupies three dimensions, being able to move freely in all directions.

In a digital design process, similar *axes of freedom* (independent variables, or parameters) define the possibility to transform an object. The entire set of virtual design iterations, composed of every possible transformation, forms a whole described by its design space, which holds a population of individual virtual designs, and features as many dimensions as it has controlling parameters. If not allowed to move or rotate, a sphere has one axis of freedom (its radius), a box has three axes of freedom (its length, width, and height), and so on. This variation within constraints is the basis for what Ernst Mayr (1959) referred to as the assumptions of population thinking, which are

> diametrically opposed to those of the typologist. The populationist stresses the uniqueness of everything in the organic world. What is true for the human species, that no two individuals are alike, is equally true for all other species of animals and plants (…) all organisms and organic phenomena are composed of unique features and can be described collectively only in statistical terms. Individuals, or any kind of organic entities, form populations of which we can determine the arithmetic mean and the statistics of variation. Averages are merely statistical abstractions, only the individuals of which the population are composed have reality. The ultimate conclusions of the population thinker and of the typologist are precisely the opposite. For the typologist, the type *(eidos)* is real and the variation an illusion, while for the populationist the type *(average)* is an abstraction and only the variation is real. No two ways of looking at nature could be more different.

The typologist defines genesis by way of transcendent essences that use morphological characteristics to classify a species. AAA sides instead with the populationist, who defines genesis by way of morphogenetic processes. Within a population, each individual is different from the other, but, as Trummer (2011) notes,

> at the same time these differences among individuals sustain its difference as a species. The diversity of the individuals is critical to the entire species. And this is the reason why it is called population thinking. It needs a critical mass of different individuals in order to diversify its gene pool. In that sense, a population refers to a multiplicity as defined by Deleuze. It does not define itself as the relationship between the one and the many, it rather defines the organisation of the many itself.

We have already moved far, perhaps too far, in a certain direction in our attempt to describe an ontology helpful to the understanding and positioning of anticipatory adaptive assemblages. Having discarded essences and types, particular focus now needs to be placed on fighting off another prevalent theoretical-architectural trope, the organism metaphor, before discussing the mechanisms of multiplicities and assemblages that define AAAs.

4.3 Beyond organisms: Interiority and exteriority

Scientific domains abound with references to part-whole relationships. In physics, atoms are composed of smaller particles, such as electrons. In sociology, groups are composed of individual people. Basic arithmetic concepts such as addition and subtraction show the obvious part-whole characteristics of mathematics, while fields such as economics (agent vs market), astronomy (star vs galaxy), and linguistics (phone vs corpus) all appear to be constructed according to the same model. Such relations of constitution are even more central in biology, where molecules make up cells that make up organs that make up organisms that make up populations. But the fact that biological populations are composed of organisms does not mean that all populations – for instance the populations of architectural geometries that produce AAAs – are organisms.

Biologists that have emphasised the importance of part-whole hierarchies in living systems include Woodger (1929), Novikoff (1945), Miller (1978), Mayr (1982), Eldredge (1985), and Pavé (2006), while authors that have underscored the same principle in the cognitive sciences include Simon (1962, 1996), Newell (1990), Churchland & Sejnowski (1992), Holland (1998), and Thagard (2006). Philosophers of science have discussed how the relationship between organisation of entities at different scales might be relevant to explanations of biological and cognitive operations – see Bechtel & Richardson (1993), Thagard (1999, 2010), Bunge (2003), Craver & Bechtel (2007), McCauley (2009), and Winther (2011). Findlay & Thagard (2012) make a very interesting attempt to explain the nature of part-whole relations (which, as they point out, 'has usually been taken for granted'), and to systematically show 'how components at a lower level of organization constitute wholes at a higher level'.

It is hard to view architecture and engineering as anything but domains that involve the arrangement of many building blocks (parts) into final structures (wholes). To understand the ontological structure and status of the mechanisms employed within these two disciplines, this type of hierarchy (formally a merology) appears to be a promising subject to study. Such a position, however, demands a thorough dismissal of the organismic metaphor mentioned above, the idea – postulated for instance in c (1860) and Ratzel (1891) – that a building, or a city, by analogy is organised and operates much like an organism, in which bodily organs carry out combined work to sustain the functioning of, say, a human body. As noted in Mallgrave (2006), this trope, an 'organic' theory of functionalism, would later have a very strong impact on American architects such as Louis Sullivan, who confidently stated in Sullivan (1901) that 'if the work is to be organic, the function of the parts must have the same quality as the function of the whole'. This focus on the organismic metaphor, extensively analysed in Steadman (1979), started to inform architecture theory around the mid-19th century, as articulated, for instance, in Greenough (1852):

> in art, as in nature, the soul, the purpose of a work will never fail to be proclaimed in that work in proportion to the subordination of the parts to the whole, of the whole to the function.

But this 'physiological hypothesis,' notes Rossi (1984), is 'as brilliant as it is inapplicable to the structure of urban artifacts and to architectural design'. However, whether the organism analogy is pertinent to ADs is not what is really at stake here. The real difficulty with the metaphor of the building as organism is, to quote DeLanda (2006), that beyond this simple trope hides a more sophisticated argument that is 'much harder to eliminate':

> a general theory about the relations between parts and wholes, wholes that constitute a seamless totality or that display an organic unity. The basic concept in this theory is what we may call relations of interiority: the component parts are constituted by the very relations they have to other parts in the whole. A part detached from such a whole ceases to be what it is, since being this particular part is one of its constitutive properties.

This critique of the Hegelian seamless totality – this notion of *Totalität* was one of Georg Wilhelm Friedrich Hegel's basic concepts: only the whole is true, and every partial stage or phase is per definition partially untrue, see Vouros (2014) – was indeed tackled head on already in Deleuze & Guattari (1972):

> We no longer believe in a primordial totality that once existed, or in a final totality that awaits us at some future date. We no longer believe in the dull gray outlines of a dreary, colorless dialectic of evolution, aimed at forming a harmonious whole out of heterogeneous bits by rounding off their rough edges. We believe only in totalities that are peripheral. And if we discover such a totality alongside various separate parts, it is a whole of these particular parts but does not totalize them; it is a unity of all those particular parts but does not unify them; rather it is added to them as a new part fabricated separately.

Following his philosophical forerunners, DeLanda (2006) targets the idea that 'parts' constitute a 'whole' that forms a *seamless totality* analogous of a body constituted by organs. As he points out, such a part (an organ) ceases to meaningfully exist outside of the whole, an arrangement sustained by what DeLanda calls *relations of interiority*. (In DeLanda (2016) this idea is exemplified further through the observation that one can only be a father if one is related genealogically to a son or a daughter, and vice versa – the identity of being a father or son or daughter cannot exist outside this mutual relation.) DeLanda takes issue with such a proposition because a) it prevents an analysis of contingent interactions between the parts of the whole, and b) it prohibits an investigation of the emergent properties that arise from the complex whole.

Instead, DeLanda proposes an understanding of wholes based on *relations of exteriority*. In such a scheme, the parts retain a certain autonomy vis-à-vis other parts as well as the whole at large. The focus is shifted from the inert *properties* of the component parts to their more active relational *capacities* to interact with each other. A part can thus be detached from one whole only to be attached to another, unplugged from the first and then plugged into the next, the way one piece of a Lego car can be dismantled and turned into the starting point for a Lego helicopter. The Lego piece still retains its defining *properties* (such as its materiality, dimensions and colour), but it is now capable of realising entirely different *capacities* (the capacity to become a helicopter instead of a car). We shall return to the topic of capacities in the next section below. The terms 'interiority' and 'exteriority,' states DeLanda (2016), are

> somewhat misleading because they suggest a spatial relation, a relation internal or external to something. A better choice would be intrinsic and extrinsic, but the intent is clear: if a relation constitutes the very identity of what it relates it cannot respect the heterogeneity of the components. […] The majority of relations in the world are extrinsic.

If the majority of relations in the world are extrinsic, then the majority of relations involve *assemblages*. This primary theoretical alternative to a seamless organic whole is characterised in part by its use of mechanisms of extrinsic relationships. Before we discuss assemblages, however, we need to investigate the realm of 'ideal events' described in Deleuze (1969), the zone of events that give birth to assemblages. That is, we need to discuss the nature of *multiplicities*.

4.4 The birth of space: Multiplicities

The following AAA account of DeLanda's generalised Deleuzian ontology – which developed a general ontological account of individuation (morphogenesis) within multiplicities as well as the maintenance of individuated forms (as assemblages) – is aimed at extending and repositioning it through a reading that adds new dimensions to the structure of assemblages, discusses the synchronic/diachronic calibration of multiplicities, and provides an anatomy of the AAA ontology as nested double articulations.

It begins with the perhaps obvious yet rarely articulated observation that the Deleuzean notion of multiplicity pertains to the *genesis* of form (which might be viewed as architecturally synonymous with *space;* henceforth, the two terms will be used interchangeably), while the concept of an *assemblage* relates to the processes that maintain the identity of that form. As explained in Deleuze & Guattari (1980), how something comes together and how it operates once it does are quite different issues. A rare exception to the rule is Buchanan (2017), who states that the notion of an assemblage 'refers to a state of being, not its actual process of composition'. (As DeLanda notes in Delanda & Harman (2017), if the components that make up an object 'cease to interact (for whatever reason), the object ceases to exist'.) This section and the next examine in closer detail the mechanisms at work in this two-fold operation one by one.

What is the genesis of form? How can there be individuated forms in the world? What are the morphological mechanisms at work in the production of formation, the conceptual and material machinery engendering and guiding its geometric evolution? How and where is space born?

The latter of these questions might simultaneously be the easiest and the hardest to answer. In Deleuzian, DeLandian, and AAA ontology, space is born within a multiplicity. And where exactly is this multiplicity? Everywhere. Still not an entirely satisfactory explanation.

But let us scrutinise it more carefully, and see if such a closer inspection of the processes at work within the multiplicity begins to reveal some answers to the questions posed above. We have already concluded that the multiplicity replaces essences, allowing entities to be defined by the morphogenetic processes that gave rise to them, rather than as representing timeless categories, making them historically constituted *results of a selection process*. The example most obvious to us today is perhaps that of natural selection, which ‘produces’ a species by subjecting the members of a population to various pressures while they are reproductively isolated from members of other species. According to Mayr (1982), a species is thus ‘a reproductive community of populations (reproductively isolated from others) that occupies a specific niche in nature’.

Importantly, these morphogenetic processes operate without the involvement of any transcendent factors (such as essences, or God), using, as DeLanda (2002b) notes, ‘exclusively form-generating resources which are *immanent* to the material world’. Such form-generating resources are immanent to the material world by being immanent to multiplicities. Such multiplicities have a variable number of dimensions and *an absence of a higher (supplementary) dimension* that imposes an extrinsic order. To quote Deleuze (1968), in all cases the multiplicity ‘is intrinsically defined, without external reference or recourse to a uniform space in which it would be submerged’.

This is still unsatisfactorily elusive. How do multiplicities relate to the physical processes that generate material objects? Let us examine this question by way of two parallel examples, attempting to elucidate the mechanisms at work in the generation of, on the one hand, a form in nature, and, on the other, a synthetic AAA form digitally produced using a computer.

One way of beginning with the latter would be to study the way each turn of the faces in a digital model of the popular Rubik’s cube puzzle creates a permutation of its surface colours. But let us imagine instead the modelling of a different cube, one that can be modulated (by filleting its edges) into a sphere, or vice versa, as shown in Figure 6. (This is a more pertinent example as it allows for a three-dimensional spatial modulation rather than the simple two-dimensional surface variation of the Rubik’s cube faces.) Two parameters (variables) control the cube-sphere or sphere-cube form: the first specifies the cube’s edge length (which is of course equal to the side of the bounding box of the resulting form), the second the amount of filleting. Supposing that each domain runs from 0.0 to 1.0 for a total of 11 values per parameter, the design space (the ‘feasible region,’ the set of all possible points of an optimisation problem that satisfy the problem’s constraints) contains a total of (11*11=) 121 permutations. This is of course basic combinatorics using the rule of product; what is of interest to us here is that these possible subsets that can be made from the larger set define the two-dimensional *multiplicity* associated with this parametric model. As shown in Figure 7, an edge length of 1.0 combined with a filleting of 0.3 produces a form that is isomorphic to one produced by using an edge length of 0.6 and a filleting of 0.2, but of course at different scales and producing different volumes and surface areas.

This simple example illustrates at least five aspects of multiplicities as they are viewed by AAA. The first is that while what they are made of is real, it may not be actual. The term (adopted by Deleuze following Bergson following Marcel Proust, who might in turn have followed Charles Sanders Pierce and Duns Scotus) for something that is real without being actual is *virtual*. Each of the 121 possible permutations are iterations in a continuum of virtual forms. Until we define an additional mechanism that provides the system with an

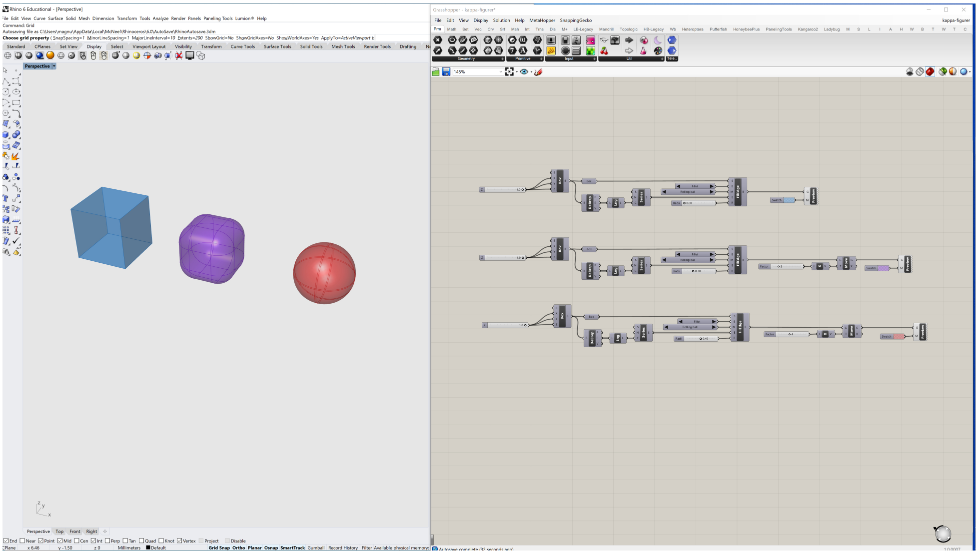


Figure 6: The cube-sphere can be modulated (by edge filleting) between the extreme states of being a perfect cube and a perfect sphere. The first parameter specifies the edge length of the form's bounding box, while the second controls the amount of filleting.

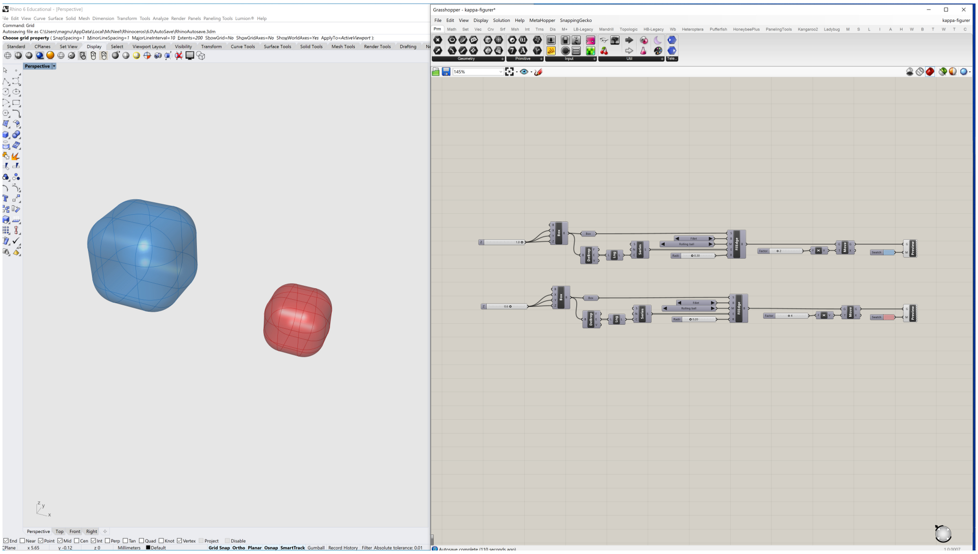


Figure 7: An edge length of 1.0 combined with a filleting of 0.3 produces a form that is isomorphic to one produced by using an edge length of 0.6 and a filleting of 0.2, but of course at different scales and producing different volumes and surface areas.

Figure 8: Sodium chloride (table salt) crystals and soap bubbles form spontaneously as their components try to meet certain energetic requirements – the latter by minimising surface tension; the former by minimising bonding energy. (Cristian V./Wikipedia Commons; AI Soot/Unsplash)

instruction for how and when to actualise (select) a form, no decision, or actualisation, will be made.

The second is that multiplicities contain whatever is needed to produce that which is to be produced: the multiplicity that produces the box-sphere or sphere-box of our example contains 121 virtual forms; the multiplicity that produces, say, a human being of course contains a much more complex set of possible permutations.

The third is that being virtual, multiplicities can coexist: the multiplicity from which the author of this thesis was constructed, for instance, at present quite happily coexists with the multiplicity from which the computer he taps these words into was constructed. While it is hard for the author and his keyboard to occupy the same space at the same time, this is not true for the box-sphere iterations, which do not need to be distributed to different locations, but whose bounding boxes can coincide and fully or partially intersect. They can even be conterminous, and can be rendered to the same space on the screen. In other words, multiplicities can be colocated and coextensive.

The fourth is that the multiplicity is defined and demarcated by its imminent constraints: in our example, no combination of parameters will produce a form in between a cylinder and a pyramid instead of in between a box and a sphere, and no parameter can be set above or below the values within its defined domain.

The fifth is that the multiplicity can be viewed – following Poincaré; see Barrow-Green (1997) – as a space of geometrical states, or phases, the same way that a phase diagram (typically used in disciplines such as physical chemistry, engineering, mineralogy, and materials science) can be used to chart thermodynamically distinct phases (such as solid, liquid or gaseous states). At any given point within the multiplicity (that is, for any given permutation), the form will exist in a particular state: at the extreme ends of the morphological gradient, those states will of course be a perfect cube and a perfect sphere, respectively. An intermediate superellipsoid form exactly in between the cube and the sphere might exist within this multiplicity; those three extremes may exemplify *singularities* that can act as *attractors* for the process *trajectories* through the space of possible states described by different parameter settings.

This latter aspect is not yet well illustrated by our example, as it features no immanent desire to guide its trajectories, but we can easily imagine such a desire being built into the multiplicity: if two *objectives* are defined, that favour for instance a particular volume and a minimisation of the resulting form's surface area, the system will gravitate towards more spherical shapes (as between a cube and a sphere of the same volume, a sphere has a smaller surface area).

Having established this simple principle of combining parameters to produce digital forms by way of constraining factors together with objectives that drive the system towards singularities within the multiplicity, and learned more about the anatomy of the latter in the process, let us turn to the question of how similar processes produce forms in nature. Rather than a form morphing between sphere and cube, we will exemplify these mechanisms using two forms constructed from two coexisting multiplicities: a (spherical) soap bubble and a (cubic) common salt crystal, as shown in Figure 8. These are examples of what DeLanda (2002b) describes as 'a large number of different physical structures which form spontaneously as their components try to meet certain energetic requirements'. The soap bubble is constrained to seek a point of minimal free energy by minimising surface tension; the salt crystal adopts the form of a cube by minimising bonding energy. As DeLanda goes on to note, we can imagine the state space of the process leading to these forms

> as structured by a single point attractor (representing a point of minimal energy). One way of describing the situation would be to say that a *topological form* (a singular point in a manifold) guides a process which results in many different physical forms, including spheres and cubes, each one with different *geometric* properties. This is what Deleuze means when he says that singularities are like 'implicit forms that are topological rather than geometric'. This may be contrasted to the essentialist approach in which the explanation for the spherical form of soap bubbles, for instance, would be framed in terms of the essence of sphericity, that is, of geometrically characterized essences acting as ideal forms.

Singularities, or attractors, are a set towards which a dynamical system evolves over time; points close enough to the attractor remain close even when slightly disturbed. Such points determine the long-term tendencies of and structure the possibilities available to a physical process as it traverses the state space. The mechanism that produces a soap bubble is quite different from that which produces a salt crystal, but they are both *minimising* processes. This *mechanism-independence* substitutes events in the place of essences, as the process of minimising something (which can also be viewed as the *desire* to minimise something, or as the *effect* that something is minimised as a *result of a set of circumstances)* constitutes the event of producing a new form, as opposed to producing a copy of an existing essence.

Another simple example may serve to show how this principle of *universal* (mechanism-independent) processes organised by singularities produce form. A river typically begins as a tiny stream running down a mountain slope. Fed by rainwater as well as melting snow and ice, the water gravitates downhill, following cracks and folds in the mountain topology as it flows towards lower ground. Not only the point where the trajectory ends (typically the river will take a winding route and widen before emptying out into the sea) can be viewed as a singularity or attractor point, but also those topological features that make the water change direction and pick up speed along the way. As circumstances shape the landscape (for instance through weather events, or by the impact of the water itself as it wears away rock and carves out a network of valleys), attractors may be dislocated, or even disappear altogether. An even simpler example is the fixed-point attractor at the base of a bowl. A marble is flicked in motion, sliding up and down the sides of the bowl until it settles and ceases moving at the bottom of the bowl, the singularity towards which the bowl-marble system evolves over time.

Using this latter example, Bryant (2011) asks: do attractors *do* anything? This is a pertinent, but also perhaps a wrongly-posed question: the answer might be that they don't have to *do* anything (act) to do something (produce a change). In the river example above, the attractors simply *are,* 'acting' as thresholds, obstacles, barriers to the flow of water. In the bowl example, the attractor 'acts' as (distinguishes) the centre of gravity. The singularities within the multiplicity, by way of their sheer existence, arrange the trajectory of the form as it progressively differentiates toward its final state.

To reiterate, these morphogenetic concepts – the notion of multiplicites and the idea of singularities – are evoked to eliminate essences. Should anyone still be undecided as to the point of the schema, Deleuze (1968), substituting 'idea' for multiplicity, states plainly that

> Ideas are by no means essences. In so far as problems are the object of Ideas, problems belong on the side of events, affections, or accidents, rather than of theorematic essences […] Consequently the domain of Ideas is that of the inessential.

The difference between essence and multiplicity can be viewed as the fundamental difference between preformation and preprogramming. DeLanda (2002b) illustrates this situation with a metaphor of embryogenesis. Essentialist interpretations view this unfolding of a fertilised egg into a fully developed organism, complete with differentiated tissues and organs as following a *preformed* schema (those tissues and organs are already given in the egg). Most biologists today agree that this is incorrect, and that differentiated structures emerge as the egg develops. As Deleuze might say, the embryo's singularities come in sets that are structured so as to progressively specify the nature of their multiplicity as the embryo evolves. (The egg is *preprogrammed* to develop into an organism.) Similarly, we may say that the singularities within a AAA are structured, or preprogrammed, to progressively develop into a final form.

DeLanda (2002b) extends his explanation by evoking two mathematical concepts: group theory and invariants. The set containing rotations by 90 degrees forms a group, he explains, and the importance of groups of transformations is

> that they can be used to classify geometric figures by their *invariants:* if we performed one of this group's rotations on a cube, an observer who did not witness the transformation would not be able to notice that any change had actually

> occurred (that is, the visual appearance of the cube would remain invariant relative to this observer). On the other hand, the cube would not remain invariant under rotations by, say, 45 degrees, but a sphere would. Indeed, a sphere remains visually unchanged under rotations by *any amount* of degrees. Mathematically this is expressed by saying that the sphere has *more symmetry* than the cube relative to the rotation transformation.

Such a classification of geometries by their degree of symmetry is obviously quite different form the traditional essentialist approach. The geometries are now classified, notes DeLanda, 'by *their response to events that occur to them'*. Two conclusions can be drawn from this: 1) entities are classified not by an intrinsic property but by a property (degree of symmetry) relative to a specific transformation, and 2) since the group of transformations of one entity (the sphere) is the subgroup of another (the cube)

> it becomes possible to envision *a process which converts one of the entities into the other* by losing or gaining symmetry. For example, a sphere can 'become a cube' by loosing invariance to some transformations, or to use the technical term, by undergoing a *symmetry-breaking transition.*

This is of course nothing less than a description, albeit using a different terminology, of the parametric transformation from cube to sphere and back again that we have already carried out above. We shall return to the breaking of symmetries in a moment, but let us first consider the virtual dimension within which these symmetries are broken. DeLanda points out that the same process brings about physical transmutations such as phase transitions, which switch physical systems from one state to another, the way water changes at critical points. As we all know, under normal circumstances water has a tendency to freeze into ice at 0 °C, spontaneously self-organising into crystals, and to turn into vapour at 100 °C, eventually evaporating into the surrounding air. If the water is never allowed to reach those singularities, this *tendency* is still real – it is an unexercised tendency. It is a potential, something that could happen. It is *virtual*.

The metaphysics developed in Deleuze (1968) can be summarised as one in which multiplicity replaces substance, event replaces essence, and virtuality replaces possibility. The discussion about substance – originating with a highly creative reading of the innovative linguistic theory presented in Hjelmslev (1943) – is not crucial to the present argument; let us instead turn to the ideas of the event and the virtual. Deleuze (1966) develops the philosopher's concept of virtuality, which precedes his notion of the multiplicity, outlined in the same book. Working our way backwards, we begin by noting the definition of the virtual as that which is real but not actual. To understand this, we need to make a distinction between *properties* (that are always actual) and *capacities* (that can be virtual). In his books and lectures, DeLanda is quite consistent in his (dramatic) use of a knife to exemplify this, and we may as well follow his lead.

Properties endure and oscillate; they are always actual. Our knife may be either sharp or blunt. A property is thus the *state* of something: 'the knife is sharp'. Capacities need not be actual, but can become so. When a capacity becomes actual, it is never as a state, but always as an *event*. The actualisation of the capacity to cut is an event that happens to something that is being cut, that is, it is a double event (Deleuze calls this *puissance)*. The capacity to affect (in the case of the knife, the capacity to cut) has to be coupled with something that has the capacity to be affected (something that can be cut). Capacities are therefore always *relational.* The difference between a capacity (a real potential) and a capacity being exercised (the actualisation of the potential) is the difference between the virtual and the actual.

A virtuality is the space of possibilities associated with a particular multiplicity. In practical AAA terms, the multiplicity is given (similarly to how the mountain the river meanders down is given): it is its own prerequisite, synonymous with the sum total of the aggregated particulars of the project at hand. As we saw with the river carving away singularities as it wears away rock over time, the fact that the multiplicity is given does not mean it cannot change (indeed, this change is per definition constant, as the world's progress cannot be halted). A proper investigation of the mechanisms responsible for such change would be very helpful but is beyond the scope of this thesis; here it may suffice to point out that in AAA theory, such mechanisms come in at least two guises: synchronic and diachronic change.

These linguistic terms, borrowed from de Saussure (1916), in this case refer to the change in the anatomy of the multiplicity that on the one hand arises from the present project (synchronically, at a moment in time without taking its history into account), and on the other from its circumstances over time (diachronically, considering its evolution and development through history). The multiplicity can change synchronically for instance by a change in the available resources (such as a new member added to the design team bringing additional skills). The multiplicity may change diachronically both 'within' and 'outside' the project. Examples of the former would include the same AAA being used for an extended period of time, with changes in its historical context rearranging its underlying multiplicity, as when a succession of legislative adjustments delimits the possibilities in various new ways over time, or when a change in the physical context arises (for instance if new buildings that overshadow the AAA are added in its immediate vicinity). Examples of the latter would include various progressions at larger scales: technological change may introduce new possibilities of an infrastructural or computational character (faster processors, better software), climate change may call for new simulation techniques and values, inventions in materials science may lead to unprecedented opportunities as today's conservative range of building materials is expanded to include novel components that achieve additional performance targets (as outlined in Paper III), and so on.

Before concluding this section on morphogenesis, let us revisit the breaking of symmetries by briefly touching upon the process of *progressive differentiation* alluded to above, what we might call the *trajectory of individuation.* DeLanda (2002b) considers the phase transition at which water changes from ice to liquid, or from liquid to steam, noting that the broken symmetry aspect shows when a perfectly uniform gas is compared to a perfectly crystal solid:

> In these ideal conditions, the gas would display invariant properties under all translations, rotations and reflections, while the solid would be invariant to only a subset of these transformations.

The progressive differentiation of the egg in the example above is another representative case of how the breaking of symmetries differentiates forms progressively, through what

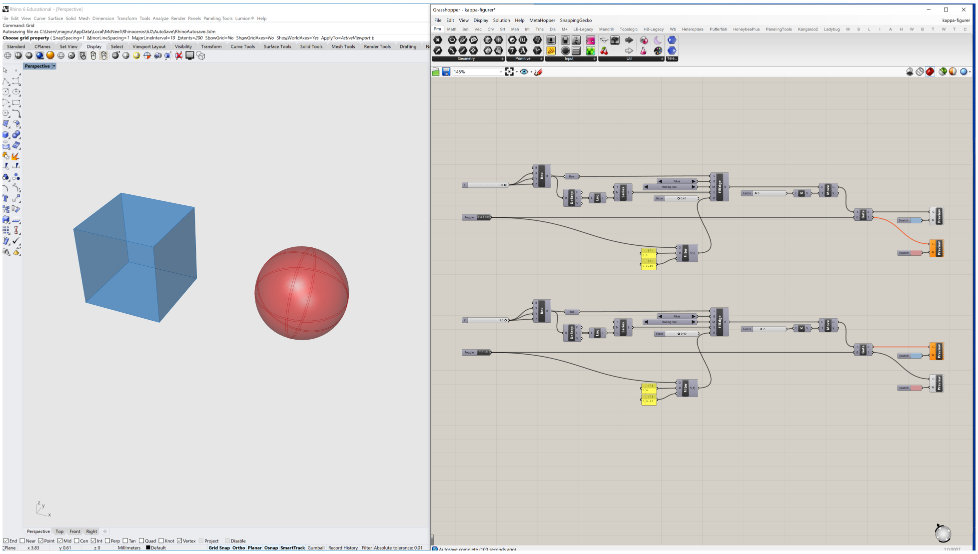


Figure 9: Simplified to two singularities, the sphere-cube model oscillates between the state of being a perfect sphere and the state of being a perfect cube.

DeLanda calls ‘a complex cascade of symmetry-breaking phase transitions’. This idea can be translated into the state-space terms of the multiplicity by noting that a singularity (or set of singularities) can undergo a symmetry-breaking transition and be converted into another singularity or set of singularities, an event known as a *bifurcation*.

We can use our parametric sphere-cube example to illustrate this. In practical terms, we model this parametric form (in Grasshopper) using two ‘sliders’ (analogous to the slide potentiometers used for instance in audio equalisers) that control the form’s dimensions and degree of filleting. To quote DeLanda (2002b), the sliders ‘determine the strength of external shocks or perturbations to which the system being modelled may be subject‘. A change in these slider values produces a new permutation within the AAA’s domain of virtual forms. As we lower the amplitude of the filleting (control) parameter from its maximum value (that is, as we initiate a symmetry-breaking cascade to allow the form to progressively differentiate ‘towards’ a cube), we move across critical values (DeLanda speaks of ‘thresholds of intensity’) at which bifurcations break the prior symmetry of the system. Since in our example, every new slider setting produces such a bifurcation, it might be easier to grasp the key concept if one imagines their respective domains as running not from 0.0 to 1.0 for a total of 11 values per parameter, as outlined above, but rather from 0.00 to 1.00 for a total of 101 values per parameter, but with an unchanged feasible region, that is, with symmetries breaking only at the points (singularities) 0.0, 0.1, 0.2, and so on.

If for ‘permutation’ we substitute ‘state’ (the state of the form being its relative sphere-ness or cube-ness), and if, as shown in Figure 9, we simplify the model to hold only two singularities, it will oscillate between the state of being a perfect sphere and the state of being a perfect cube as we change the slider values. Bifurcating these singularities introduces additional critical points at which the system exhibits new states, progressively differentiating forms in between sphere and cube. Indeed, the act of setting the first slider (controlling dimensionality) to a new value and then setting the second slider (controlling filleting) to a new value constitutes such a bifurcation. It is easy to imagine how a row of sliders being progressively set to new values (a slider changing the colour of the form, another changing its rotation in space, and so on) produce a cascade of bifurcations, with each slider adding a dimension to the optimisation process, and each calibration differentiating a new form from the virtual domain of the multiplicity.

While mathematical models are mechanism independent, in physical systems such as those of the soap bubble and the salt crystal discussed above, the cascades of bifurcations that give rise to differentiated forms are dependent on specific (physical) mechanisms. As Goodwin (1990) points out, 'many pattern-generating processes share with developing organisms the characteristic that spatial detail unfolds progressively simply as a result of the laws of the process'.

The mechanism independence of a multiplicity (what Deleuze refers to as its *universality)* is highly significant as it turns it into a *concrete universal*. This idea that the virtual does not resemble the actual is developed in DeLanda (2002b) into a description of

> concrete sets of attractors (realized as tendencies in physical processes) linked together by bifurcations (realized as abrupt transitions in the tendencies of physical processes) […] the universality of a multiplicity is typically divergent: the different realizations of a multiplicity bear no resemblance whatsoever to it and there is in principle no end to the set of potential divergent forms it may adopt […] multiplicities give form to processes, not to the final product, so that the end results of processes realizing the same multiplicity may be highly dissimilar from each other, like the spherical soap bubble and the cubic salt crystal.

This has another important implication already touched upon above – multiplicities are not sharply distinguished entities that exist side by side the way essences are envisioned. Rather, they coexist and overlap: we can make a copy of the sphere-cube definition in the computer, and change the slider settings of one of them, which will produce two permutations partly occupying the same space, produced by what DeLanda (2002b) refers to as 'concrete universals (…) *meshed together into a continuum'*. Deleuze (1968) writes that multiplicities coexist 'but they do so at points, on the edges, and under glimmerings which never have the uniformity of a natural light. On each occasion, obscurities and zones of shadow correspond to their distinction'. A *continuous* space, the multiplicity, is thus progressively differentiated to define *discontinuous* spaces.

Again, a phase transition may illustrate this, based on an understanding of different kinds of physical properties. An *extensive* property is one that is intrinsically divisible. Deleuze & Guattari (1980) argue that an *intensive* property cannot be divided without causing a qualitative change. Dividing a body of water at a temperature of 90 degrees will not produce two bodies at 45 degrees, but if we create a temperature difference within the container that holds the water (for instance by heating it from below) we 'divide' it into different temperatures at the top and bottom. As we gradually differentiate the intensive space through a cascade of broken symmetries (produced by increasing the temperature), we differentiate it progressively towards the singularity (boiling point) at 100 °C, where the bifurcation gives rise to a new extensive structure (gas). This is the *morphogenetic* view of the relation between an undifferentiated (topological) and a differentiated (metric) geometry. Paper IV and Paper V use 'auxiliary loads' ('hidden' properties and capacities pertaining to materials, as for instance their global warming potential, cost, or resistance to weathering) to progressively differentiate metric geometries.

While AAAs are fuelled by mathematics, here is an important difference between a mathematical model and a AAA. Mathematical models, as DeLanda points out in Delanda & Harman (2017), are 'never of actual objects, not even simple ones like water vapor, let alone dogs and trees. A math model captures dependencies between the way properties change (and that is a piece of information worth having), but to do so they must simplify enormously the phenomena they model'. While the AAA is a mathematical construct that may be viewed as a simplification in that, weary of the curse of dimensionality discussed in Paper IV and Paper V, it seeks to use as parameters (singularities) only the values most crucial to a successful outcome, it is not a model *of* something, but rather, to keep with the river example used earlier, a 'variable topography' guiding the trajectory of individuation. Viewed in this way, *form follows probability:* the river becomes a statistical form, with the probability of a change in trajectory at each bifurcation point guiding its progressive formal differentiation. While AAA focuses on the *evolutionary* history of the geometry, that is on the *fitness* of forms, it should be noted that the typical yardstick used in genetics – reproduction – is simultaneously a measure of this aggregated bifurcation probability as the form unfolds within the multiplicity (as at every bifurcation point the probability of reproductive success is updated).

We can now begin to answer the questions that opened this section. The genesis of form is 'pre-programmed' into the multiplicity within which it is produced, in the same way that the meandering path of a river is 'pre-programmed' into the very topology of the hill it runs down on its way from mountain top to basin. Forms in the world result from physical actualisations of virtual forms that the structure of the multiplicity allows; they are self-organised effects of contextual pressures. The morphological mechanism at work is a search for preferable singularities within the multiplicity, an optimisation process based on objectives that guide the geometric evolution of the form towards a preferred state. Space is born when the process trajectory within the multiplicity produces a new state that is deemed preferable to other states, given some objectives. Space is born within the multiplicity, by the multiplicity, as an actualisation of one of the virtual permutations of the multiplicity. As the examples of flows show, there is nothing transcendent or mystical about such a progression: it is simply a consequence of the anatomy of the multiplicity, or, as Goodwin noted above, 'a result of the laws of the process'.

Consider again the soap bubble, a hollow sphere constructed from air enclosed by a very thin film of soapy water. This bubble has at least three features that are shared by all forms discussed in this section. The first feature is that its materials constitute a set of heterogeneous components. But even if it were made from a homogeneous substance, the soap bubble's form would be the result of a heterogeneous set of 'parameter settings,' that is, its composition features more than one axis of freedom. The second feature is that the bubble has a history: it is born from a multiplicity of virtual bubbles (of different radii and film thicknesses, at different positions, with different velocities and trajectories, and so on) at a specific point in time, and it will die at some later instance (when the water inside the micrometer-thick soap film that constitutes its surface drains or evaporates to break the surface tension that holds it together). The third feature is that the bubble, in all its iridescent glory, is more than the sum of its parts. It exhibits emergent properties: assumes the shape of the least surface area possible containing its given volume, appears to gradually change colour with differences in the angle of illumination, can be considered an analog computer, makes children happy, and so on.

Deleuze, DeLanda, and AAA have a name for such historical entities composed of heterogenous parts and producing emergent properties. They are called *assemblages.*

4.5 The maintenance of space: Assemblages

Following our attempt to elucidate the mechanisms that give birth to space, let us now turn to the question of how those spaces retain their identity, how an object's components maintain their interactions in such a way that the object may continue to exist. We noted above that one aspect that defines assemblages is their reliance on mechanisms of extrinsic relationships. What are the other characteristics of an assemblage? What is the 'glue' that holds the components together? And how is it that assemblages seem to display properties beyond those that we find in its components?

In DeLanda (2002b, 2006, 2011, 2016), four very well-argued treatises positioned at the confluence of Deleuzian philosophy and a range of theories about phenomena such as complexity and emergence, the philosopher lays the foundation for his theory of assemblages. *Intensive Science and Virtual Philosophy; A New Philosophy of Society: Assemblage Theory And Social Complexity;* the appendix to *Philosophy and Simulation: The Emergence of Synthetic Reason;* and *Assemblage Theory* constitute the primary source material for anyone wishing to understand this concept.

The term *assemblage* is derived from ideas predominantly outlined in Deleuze & Guattari (1980). This book, *A Thousand Plateaus: Capitalism and Schizophrenia*, is a philosophical tracing of the inflection points that somehow connect profit to psychosis, written by Deleuze together with his philosophical companion, psychotherapist Félix Guattari. The term, notoriously hard to translate, is a controversial transliteration of the French word *agencement*. As DeLanda (2016) notes, an initial challenge presented for anyone writing on the topic is thus one of terminology, but as he is quick to point out, a second difficulty is posed by 'the fact that the concept is given half a dozen *different definitions* by its creators'.

According to Sassen (2008), the English translation 'assemblage' means 'a contingent ensemble of practices and things that can be differentiated (that is, they are not collections of similar practices and things) and that can be aligned along the axes of territoriality and deterritorialization,' a definition that already demands some knowledge of Deleuzean terminology. We shall return to these 'axes' below. Providing an alternative and very brief definition that does not assume this prior knowledge, DeLanda (2006) offers that assemblages form a theory 'meant to apply to a wide variety of wholes constructed from heterogenous parts'. In an interview, Deleuze & Parnet (2007), Deleuze himself, in his trademark scientific-poetic style, described the concept thus:

> What is an assemblage? It is a multiplicity which is made up of many heterogeneous terms and which establishes liaisons, relations between them, across ages, sexes and reigns – different natures. Thus, the assemblage's only unity is that of a co-functioning: it is a symbiosis, a 'sympathy'. It is never filiations which are important, but alliances, alloys; these are not successions, lines of descent, but contagions, epidemics, the wind.

So the assemblage establishes relations between non-uniform parts, and fits them together by actively linking them to each other. But this is still quite vague. As noted in DeLanda (2016), the English term 'fails to capture the meaning of the original *agencement,* a term that refers to the action of matching or fitting together a set of components (agencer), as well as to the results of such an action; an ensemble of parts that mesh together well'. What would be an example of such a well-meshed ensemble? DeLanda (2002b) provides a good image in

> the assemblage which a walking animal forms with a piece of solid ground (which supplies it with a surface to walk) and with a gravitational field (which endows it with a given weight). Although the capacity to form an assemblage depends in part on the emergent properties of the interacting individuals (animal, ground, field) it is nevertheless not reducible to them. We may have exhaustive knowledge about an individual's properties and yet, not having observed it in interaction with other individuals, know nothing about its capacities.

Before we move on, we need to address the elephant in the room. What exactly *are* assemblages? They are what Buchanan (2017) call the *arrangements* that make up life, the universe, and everything. To quote Harman (2008), 'DeLanda conceives of the world as made up of countless layers of assemblages, irreducible to their parts and never dissolved into larger organic wholes'. In other words, assemblages are everything that we encounter and interact with, from gluons to galaxies, and including elephants and rooms.

Every material entity – an atomic particle, a human being, a language, a wooden desk, a doctoral thesis, an intention to meet deadlines – is an assemblage. Each of these entities has a unique history (a date of birth and at least a prospective date of death) and a composition that combines heterogenous parts through extrinsic relationships, components that are themselves assemblages. An assemblage thus isn't necessarily limited to a 'single membership' status simply because it happens to be a component part of a particular assemblage: a human assemblage might for instance simultaneously be both a parent and a child, and (if it has dual citizenship) a component part of two different nation states – as well as a part of humanity, an engineer, a Chelsea supporter, a coffee drinker, and one of the users of a building. This nesting of assemblages provides our material reality with a heterogenous and interconnected quality. It also makes it obvious that the assemblage cannot dissolve into a larger organic whole, as if it stopped supporting Chelsea (that is, if it detached a component part), it would still function and retain most of its identity.

But despite potentially being part of several assemblages at the same time (as in the case of our combined parent-child assemblage with its dual citizenship), each assemblage is nevertheless a singular individual, a contingent unit, an *emergent whole,* with an identity shaped by a particular historical process that brought together its components through what DeLanda calls emergent mechanisms, which provide an assemblage with properties that are more than the sum of its parts, hence irreducible to those parts. The soap bubble can make children happy because its surfactant component (soap) consists of a metal salt with a long fatty acid tail attached to it, and at some point (when submerged in water), this salt ionised, leaving the tail attached to one of the ions, which interacted with other similar ions to create a higher surface tension (due to the hydrophobic nature of the fatty acids) than would otherwise be the case, a process that produced the spherical form and allowed the solution to hold this shape even after most of the interior solution drained out of the bubble. We will study the emergent nature of such assemblages in further detail in a moment.

As mentioned above, yet another example of an assemblage would be a language, which Deleuze and Guattari outline a general theory of in *A Thousand Plateaus,* as discussed by Bogue (2003):

> …Deleuze and Guattari insist that language is a mode of action, a way of doing things, and the condition of possibility of any language is the complex network of practices and material elements that shape a given world. This complex network is made up of what Deleuze and Guattari call 'assemblages' (agencements), heterogeneous collections of actions and entities that somehow function together. These may be divided into two broad categories that function as a level of content and a level of expression, the first consisting of non-discursive machinic assemblages of bodies, 'of actions and passions, an intermingling of bodies reacting to one another,' the second of discursive collective assemblages of enunciation, 'of acts and statements, of incorporeal transformations attributed to bodies' […] Machinic assemblages are the various patterns of practices and elements through which a world's bodies are formed, and collective assemblages of enunciation are the patterns of actions, institutions and entities that make possible linguistic statements.

In other words, assemblages operate across different modes and scales: they can be highly abstract or very concrete, or both. An assemblage may be quite minuscule, such as, say, the interconnected anatomical system in a single human being that we know as the *ossicles* – an assemblage of three tiny bones in the middle ear that together receive, amplify, and transmit sound from the eardrum to the inner ear – or it may encompass the entire population of human beings in the world. Writes Colebrook (2006):

> Rather than consider 'man' as a being who goes through time, such that time would be homogenized from the point of view of a single humanity, Deleuze and Guattari look at the ways in which 'man' is formed through a process of increasing generality and homogenization, with primitive and specific assemblages of bodies eventually

> forming a single body (of humanity) that commands a time that is always and everywhere of the same form and measure.

These characteristics give assemblages a reassuringly scale-independent quality that in turn provides AAAs with the means to define designs at any scale, from object to city, and at any level of component interaction, from molecular composition to infrastructural connectivity. Interconnected building blocks, in other words, that eventually – once several assemblages have made connections to each other so as to aggregate into larger assemblages – become a final structure. This sounds a lot like the pegs and inner tubes that make up the assemblage already mentioned above, epitome of playthings for budding designers, the Lego line of plastic construction toys. As discussed in Paper III, this scale-independent or, rather, scale-transgressing quality for instance opens up for obvious but rarely considered conceptual-pragmatic connections to be made between microscopic and macroscopic aspects of the material design of architectural surfaces.

The idea of an assemblage as a model of the practice (and outcome) of design is perhaps present already in Simon (1996):

> …it is typical of many kinds of design problems that the inner system consists of components whose fundamental laws of behavior […] are well known. The difficulty of the design problem often resides in predicting how an assemblage of such components will behave.

From this we may deduce that even when we don't (yet) know what the final outcome of our experimenting with the brightly-coloured Lego pieces might be, we still understand the properties and potentials of each Lego brick, the inherent system that makes them fit together. Edmonds & Bryson (2003) trace a similar trajectory in their discussion of the 'syntactic complexity' of design, the lack of a clear mapping from design to behaviour:

> If a computational system is syntactically complex then there is no easy prediction of the resulting behaviour from the initial set-up of the system. In other words, the computational distance between initial conditions and outcomes is too great to be analytically bridgeable using any short-cut. The only real way to get the outcomes is to run the system. The difficulty in bridging this gap means that there are at least two views of the system: that of the set-up of the system and that of the resulting behaviour.

Before-the-fact analysis is thus stripped of its power to predict an outcome: one has to observe the emerging performance of, in this case, a computational system in order to understand what the individually well-documented parts do when they come together in a particular arrangement or constellation. The Lego pieces in front of us never operate in isolation, but always in relation to what they might become when assembled together with some other pieces, that is, in relation to the effects of their potential interlocking with this or that other piece (that has the capacity to be interlocked). This implication of specific connections with other concepts, and the focus on the arrangement of such connections, is the first of two factors that according to Phillips (2006) make the use of the term assemblage 'disparate and sometimes imprecise'. The other factor is, again, that the translation of ‘agencement' by ‘assemblage’ can give rise to ‘connotations based on analogical impressions, which liberate elements of a vocabulary from the arguments that once helped form it’. The translation is not really a good approximation for its French counterpart. Explains Phillips:

> Agencement is a common French word with the senses of either ‘arrangement’, ‘fitting’ or ‘fixing’ and is used in French in as many contexts as those words are used in English: one would speak of the arrangement of parts of a body or machine; one might talk of fixing (fitting or affixing) two or more parts together; and one might use the term for both the act of fixing and the arrangement itself, as in the fixtures and fittings of a building or shop, or the parts of a machine.

In contrast, the word assemblage in English means more or less the same as its actual French counterpart, *assemblage,* a word that Deleuze and Guattari use less often and certainly never in a philosophical sense. And the situation becomes even more misleading in discussions about what assemblages *do*. The assemblage does not so much ‘assemble’ as *finds its position*. It is an *arrangement* imminent to the multiplicity that gives rise to it, a *positioning* relative to other positionings. It forms like a ripple in an ocean of multiplicities, like a dune in the shifting sands of a multiplicity desert. Its genesis is like that of a protostar accreting gas and dust during the gravitational collapse of a giant molecular cloud in that greatest of multiplicities known to us, the universe. It is *in* the universe and made *from* the universe. The latter example makes it easier to understand the assertion in Buchanan (2017) that ‘the assemblage *is* a multiplicity’: during the stellar evolution that produced our solar system, most of the collapsing mass formed the Sun at its centre, while the rest became planets, moons, asteroids, and so on. On planet Earth, of course, the evolution of biological populations emerged as another formal articulation of the multiplicity constituted by our tiny shrapnel of that original giant molecular cloud, and this evolution in turn took place along other multiplicity ‘planes’ or ‘levels’ nested or folded within the planetary one: the human level, the bacterial level, the cellular level, the molecular level, the genetic level, and so on.

Let us pause for a moment to consider what we have learnt about assemblages so far. Assemblages are the primary theoretical alternative to seamless organic wholes. They are nested constructs within a multiplicity, they have a historical identity, they are created and stabilised by processes that involve extrinsic relationships between non-uniform parts, and they produce emergent properties. Furthermore, their extrinsic connectivity means that a component part of one assemblage may be detached from it and plugged into a different assemblage in which its interactions will differ. An important basic condition for this system is the notion of a ‘flat ontology,’ a concept introduced in DeLanda (2002b) as an assertion that

> while an ontology based on relations between general types and particular instances is hierarchical, each level representing a different ontological category (organism, species, genera), an approach in terms of interacting parts and emergent wholes leads to a flat ontology, one made exclusively of unique, singular individuals, differing in spatio-temporal scale but not in ontological status.

In other words, while every entity is neither identical nor equally important, all entities are equally real, and always made up of populations of individuals. Returning to our example of the Lego car that might become a Lego helicopter (or indeed a Lego anything), and following DeLanda (2006), we can distinguish

> the properties defining a given entity from its capacities to interact with other entities. While its properties are given and may be denumerable as a closed list, its capacities are not given – they may go unexercised if no entity suitable for interaction is around – and form a potentially open list, since there is no way to tell in advance in what way a given entity may affect or be affected by innumerable other entities. In this other view, being part of a whole involves the exercise of a part's capacities but it is not a constitutive property of it. And given that an unexercised capacity does not affect what a component is, a part may be detached from the whole while preserving its identity.

But understanding the properties of the pieces of Lego that make up our car or helicopter assemblage, the pegs and inner tubes that constitute the pieces, the friction and tolerances that allow them to be combined with and taken apart from each other, does not explain the properties of the whole (the car/helicopter). Continues DeLanda:

> Relations of exteriority also imply that the properties of the component parts can never explain the relations that constitute a whole […] although they may be caused by the exercise of a component's capacities. In fact, the reason why the properties of a whole cannot be reduced to those of its parts is that they are the result not of an aggregation of the components' own properties but of the actual exercise of their capacities. These capacities do depend on a component's properties but cannot be reduced to them since they involve reference to the properties of other interacting entities.

Furthermore, explains DeLanda, we can analyse the role or roles that a component plays within an assemblage by mapping its relative location within two continua – 1) material/ expressive, 2) territorialising/deterritorialising:

> Assemblages are characterized along two dimensions: along the first dimension are specified the variable roles which component parts may play, from a purely material role to a purely expressive one, as well as mixtures of the two. A second dimension characterizes processes in which these components are involved: processes which stabilize or destabilize the identity of the assemblage (territorialization and deterritorialization) […] these processes are recurrent, and their variable repetition synthesizes entire populations of assemblages. Within these populations other synthetic processes […] generate larger-scale assemblages of which some of the members of the original population become component parts.

To understand this passage, we may once again shift away from Lego and return to our example of the sphere-box from the previous section. The idea DeLanda explores above, as well as (particularly) in DeLanda (2016), is that of 'using a single term, "assemblage," but building into it *parameters* that can have different settings at different times,' the same way that we constructed our parametric geometry that morphed between box and sphere.

Before moving on, let us briefly consider the rare consonance between thinking and doing, the unique congruence between theory and practice made possible by this simple act of adding control parameters to a concept, as it is one of the most useful aspects of the AAA idea. In the flat ontology proposed by DeLanda and advocated by AAA (one in which all entities are equally real and no entity can be reduced to anything else), any assemblage can be plugged into any other assemblage, as they differ in spatio-temporal scale but not in ontological status. The parameters that control the assemblage geometry might thus pertain to data flows at wildly differing scales and from highly divergent fields: pedestrian circulation at the urban scale *and* the global warming potential of a particular façade panel, live-fed stock market values *and* isovist analysis data, legal zoning restrictions *and* values from a mathematical surface equation may all be pulling the geometry in different directions.

While at any one point we may focus (for reasons of timing and context) on one or the other, there is really no difference between 'doing theory' and 'doing design' when defining a AAA. The act of designing the AAA is equivalent to the act of investigating the ontology, epistemology, methodology, and axiology of AAA theory. The design is the theory. As DeLanda puts it: 'analysis in assemblage theory is not conceptual but causal, concerned with the discovery of the actual mechanisms operating at a given spatial scale. […] the topological structure defining the diagram of an assemblage is not actual but virtual and mechanism-independent, capable of being realized in a variety of actual mechanisms'. That is, it is not causal, but *quasi-causal,* a term familiar to readers of Deleuze.

To adjust our sphere-box example to align with DeLanda's diagram of an assemblage and, by extension, what Harman (2008) calls DeLanda's 'fourfold structure of the world,' we need to add two dimensions to our sphere-box definition. That is, we need to provide it with two additional sliders, the domains of which map to two gradients between end values that represent dualisms. Let us begin by adding a first slider that controls the assemblage's degree of territorialisation and deterritorialisation. 'Territorialization,' DeLanda (2016) explains, 'refers not only to the determination of spatial boundaries of a whole […] but also to the degree to which an assemblage homogenises its own components'. What does this mean? Here is another passage from DeLanda (2006) describing this ontological axis, or dimension, which

> defines variable processes in which these components become involved and that either stabilize the identity of an assemblage, by increasing its degree of internal homogeneity or the degree of sharpness of its boundaries, or destabilize it. The former are referred to as processes of territorialization and the latter as processes of deterritorialization. One and the same assemblage can have components working to stabilize its identity as well as components forcing it to change or even transforming it into a different assemblage. In fact, one and the same component may participate in both processes by exercising different sets of capacities.

To add this dimension, we add a slider that varies the initial box geometry of the sphere-box in such a way as to trace a formal trajectory from, on the one hand, a square, to, on the other, a triangle, as shown in Figure 10. In between the two are a number of interstitial forms: the middle value represents a fully deterritorialised form (neither square nor

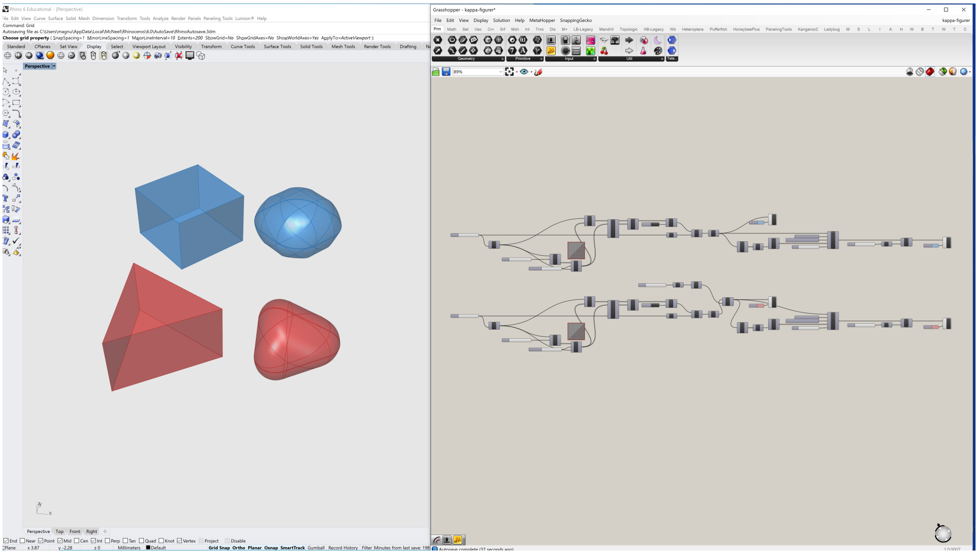


Figure 10: A slider is added that varies the initial box geometry of the sphere-box in such a way as to trace a formal trajectory from, on the one hand, an extruded square, to, on the other, an extruded triangle, producing a number of interstitial phases from a deterritorialised form (neither square nor triangle), to either a perfect square or a perfect triangle (reterritorialisation).

triangle), the setting that produces a perfect square of course is our initial value, and the setting that produces a perfect triangle represents a full reterritorialisation. Armed with these sliders, we can now produce many forms along the original dualist axis (running from box to sphere), while simultaneously affecting the geometry with our two new material-expressive/deterritorialised-reterritorialised sliders.

Adding another slider controls the material/expressive gradient. Notes DeLanda (2016):

> One dimension or axis defines the variable roles which an assemblage's components may play, from a purely material role at one extreme of the axis, to a purely expressive role at the other extreme. These roles are variable and may occur in mixtures, that is, a given component may play a mixture of material and expressive roles by exercising different sets of capacities.

We add this dimension using a topological mesh editing component that meshes our geometry, then constructs a cone from each resulting mesh vertex, as shown in Figure 11. At one extreme, this component doesn't change the underlying geometry at all, keeping its material 'untouched'. On the other, the shape becomes fully articulated with 'follicles' and coated in fur to produce an expressive effect similar to that of Thomas Heatherwick's UK Pavilion at the Shanghai Expo 2010.

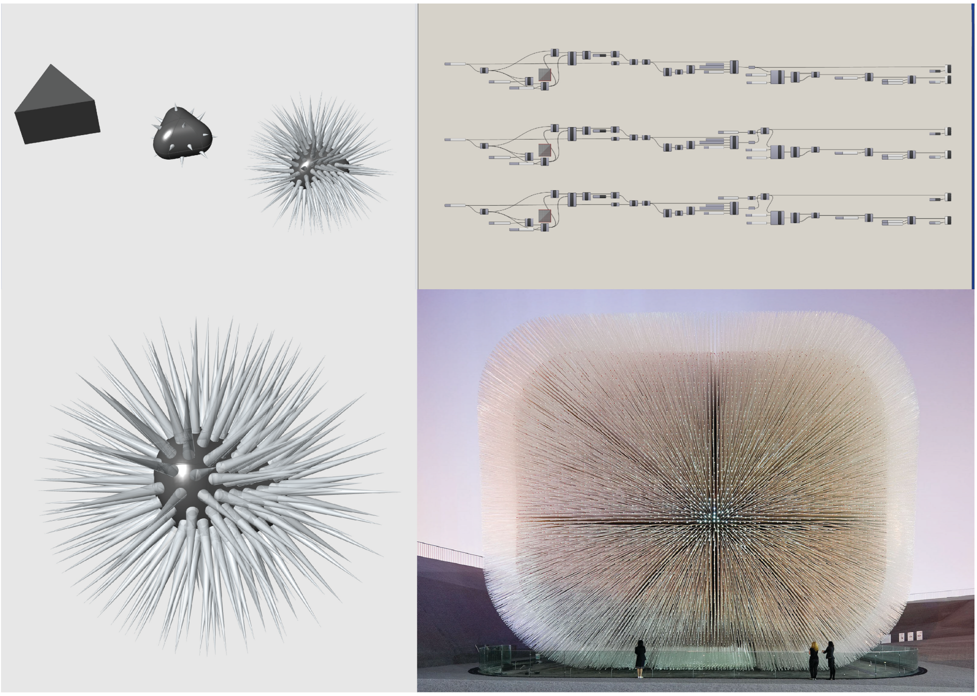


Figure 11: The geometry is meshed and cones constructed from each mesh vertex – the 'untouched' form is 'purely material,' while the fully articulated version (with cones as 'follicles' covering its entire surface) is 'purely expressive'. Note the formal similarity to Thomas Heatherwick's UK Pavilion at the Shanghai Expo 2010, commonly referred to as the Seed Cathedral. (Thomas Heatherwick Architects)

4.6 Double articulations

Deleuze and Guattari's account of the assemblage is always focused on the question 'how does it work?,' rather than enquiries such as 'what does it mean?' or 'where does it come from?'. As Deleuze & Guattari (1972) ask, 'given a certain effect, what kind of machine (assemblage) is capable of producing it?'. We can now begin to see that the morphological theory of 'double articulation' presented in Deleuze & Guattari (1980), may be used to map out the processes by which an object is produced out of other objects. Write Deleuze and Guattari:

> Articulate twice, B-A, BA . . . The first articulation chooses or deducts, from unstable particle-flows, metastable molecular or quasi-molecular units (substances) upon which it imposes a statistical order of connections and successions (forms). The second articulation establishes functional, compact, stable substances (forms), and constructs the molar compounds in which these structures are simultaneously actualized (substances).

Picking up this thread, DeLanda (2010) describes the process of double articulation

> through which geological, biological, and even social strata are formed. The first articulation concerns the materiality of a stratum: the selection of raw materials out of which it will be synthesized (such as carbon, hydrogen, nitrogen, oxygen, and sulfur for biological strata) as well as the process of giving populations of these selected materials some statistical ordering. The second articulation concerns the expressivity of a stratum.

The first articulation takes place within 'the plane of content,' and refers to the selection of a set of components by an object during its organisation, while the second articulation takes place within 'the plane of expression' and relates to the qualities that the new object embodies. Moving on, DeLanda exemplifies by showing how the synthesis of sedimentary rock in nature

> proceeds by the sorting out of pebbles of different size and composition, an operation performed by rivers that transport and deposit the raw materials at the bottom of the ocean. The loose accumulations are then cemented together and transformed into layers of sedimentary rock, that is, of an entity with emergent properties not present in the component pebbles. Then at a different scale, many of these emergent rocks accumulate on top of one another and are then folded by the clash of tectonic plates to produce a new emergent entity: a folded mountain range like the Himalayas or the Rocky Mountains.

Each AAA is fundamentally structured as two such double articulations nested within one overarching double articulation, as shown in Figure 12. The larger-scale articulation goes from space being born to space being maintained. Within the birth of space, the nested articulation is the re-ordering of a structured virtuality (the calibration of singularities within a multiplicity), while within the maintenance of space, the nested articulation is divided between the intrinsic values resulting from adaptive processes that differentiate an assemblage as an individual entity compared to its population, and the extrinsic values resulting from a combination of historical and anticipatory processes that differentiate the assemblage from all other assemblages.

4.7 AAA ontology

According to May (2005), Deleuze aims to understand 'how we might think of things in ways that would open up new regions for living'. AAA's approach to the creation of architecture aligns with Deleuze's conception of the basic nature of philosophy, which he claims begins with a question or problem, but which does not aim to find an answer or a solution so much as to create concepts with which the problem or question can be *explored,* from its presuppositions through to its consequences. As Bell (2005) notes, in a sense 'philosophers are concerned not with the question "Is this a good answer or solution?" but with the question "Is this a good question?"'. Whereas in philosophy, this attitude may at first appear to be a strategy of elusion, the philosopher dodging the bullet that carried a final resolution to the challenge at hand, in evolutionary architecture the instrumental value of this Deleuzean programme becomes clear: 'this' may indeed be a good answer, but so may 'that' and 'that' and 'that,' and being able to choose between the available alternatives demands a good question. Furthermore, asking better and better questions is the way to produce better architecture. This is what Paper I suggests in stating that as AAA-wielding ADs we

> might allow gradients of objectives to inform different – or indeed the same – parts of buildings, pit material properties against efficient circulation, structural considerations against financial implications. It might be that the most interesting results of such a model will arise from the most unexpected combinations of objectives: what is the outcome of balancing atomic structure and programmatic diversification; energy generation and speed of construction; cost and happiness?

To be able to use such questions as operational tools when creating our designs, we need to understand the mechanisms they can affect, that is, we need to understand how the spaces we design (as well as everything else in the world) comes into being and continues to exist. We need an ontological foundation, an articulation of what exists at the most basic level of phenomena. The beating heart of AAA's design philosophy is the ontology outlined above, in which two double articulations take place within a larger double articulation: space is born through an ordering of an already-structured virtual multiplicity, and is maintained through the interconnection between the interior parameter settings that articulate an assemblage as an individual entity, as well as by the exterior (counterbalancing) interactions between the assemblage and its context. The interior settings result from adaptive processes, the exterior interactions from a combination of historical and anticipatory processes. Let us conclude this chapter by reviewing eight components that begin to delineate this AAA ontology:

i) (Speculative) realism

The theses that make up AAA are, to quote the exegesis of Deleuze's project in Kleinherenbrink (2019), 'part of a systematic ontology in which a tune hummed by a philosopher on his way home is just as real as the Waal river, an electron, Frank Herbert's Dune, the city of Nijmegen, a meteor, the Wu-Tang Clan, or a bicycle'. That is, they hold first and foremost that a mind-independent reality exists – a reality beyond the world of human experience; a reality in which objects need no subjects – and secondly that individual entities are the basic constituents of that reality. AAA is not concerned with human access to the world, but with the world itself, and how it can be modulated for architectural and axiological purposes. Furthermore, AAA belongs to the *speculative realism* camp in that it holds that meaningful statements about reality can be arrived at beyond direct experience and empirical observation – by thought alone, or by simulations and other constructed models.

ii) Beyond essences: Flat ontology

As is the case with Deleuze's and DeLanda's philosophies, this systematic ontology rests on the notion of ontological equality, on what DeLanda (2002b) calls a flat ontology – one that holds that no entity can be reduced to anything else. AAA considers the entities that populate the world to be, in line with Kleinherenbrink (2019),

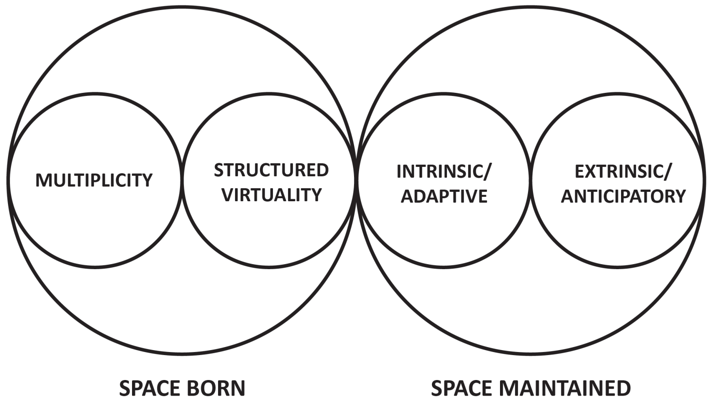


Figure 12: Each AAA is structured as two double articulations nested within one overarching double articulation. At the larger scale, space is born, then maintained. The birth of space organises a virtual multiplicity, while the maintenance of space uses intrinsic values to differentiate (via adaptation) the individual assemblage from its wider population, and extrinsic values to differentiate (via anticipation) the assemblage from all other assemblages.

> first and foremost things in themselves, which is to say forces that create their own difference in the world. This is the case for every entity […] of whatever type that we may want to consider.

Furthermore, following DeLanda (but not necessarily Deleuze) AAA rejects any notion of essences and types. The world is filled with individuals shaped by the concrete historical-genetic processes through which they emerged. As Harman (2008) notes, in such an ontology 'atoms have no more reality than grain markets or sports franchises' – and they are singular entities, not instances of an essence shared by many concrete things.

iii) Definitions all the way down

In Deleuze & Guattari (1972), this ontological equality is made manifest through a single striking line: 'Everything is a machine'. Furthermore: 'everywhere (there are) machines – real ones, not figurative ones: machines driving other machines, machines being driven by other machines, with all the necessary couplings and connections'. Deleuze (2002b) interprets the machine as being 'any system that interrupts flows'. As Kleinherenbrink (2019) explains:

> Every entity is a machine in that it has its own operations in reality. No love can be reduced to biological drives or hormonal activity, no disease can be reduced to the will of some divinity, no word can be reduced to a language, and no hurricane can be

> reduced to an expression of an overarching Nature. Instead, every love, sickness, utterance, and storm is itself a force unleashed in the world.

These machines are not driven by an over-arching ‘machine of machines,’ and they are *not* machine *metaphors*. Kleinherenbrink points out that the machine thesis is univocal, and quotes Deleuze & Guattari (1980) as saying ’there is no biosphere or noosphere, but everywhere the same Mechanosphere’. Deleuze uses at least three synonyms for these ever-present machines (which include references to concepts such as 'social machine,’ 'technical machine,’ ‘desiring-machine,’ and ‘man-horse-bow machine’): everything is (simultaneously) a rhizome, an assemblage, and a multiplicity. The variation in terminology emphasises various aspects of the machines that make up the world; as Deleuze & Guattari (1977) note, ‘they are the same machines, but it is not the same regime’. (Compare Marx’s dictum that men make their own history, but not under self-selected circumstances.)

In an attempt to move away from seemingly anthropocentric terms such as ‘machine’ and (perhaps) ‘object,’ in AAA terminology, the term ‘definition’ – borrowed from visual programming in general and the Grasshopper programming environment in particular, where the basic entity, a file holding an algorithmic program, is called a definition – replaces that of ‘machine’. Since this is an established term, it should be noted that when used in the ‘assemblage’ mode (see the next section below), we are referring to a particular kind of definition, which at a minimum features a parametric form seed, driven by in data (including the potential to use anticipatory parameters), controlled by an (adaptive) evolutionary solver, and producing associated out data. Future studies could focus on establishing protocols for other modes.

iv) Eliminating diagrams and cosmic planes: Definition modes

While AAA and DeLanda’s assemblage theory are both antithetical to essentialism, they differ with regards to the absolute separation drawn by the latter between species and genus. In the binomial nomenclature (‘two-term naming system’) used in sciences such as zoology and botany, each name of a living thing is composed of two parts: the generic name that identifies the genus, and the specific name that identifies the species within that genus. According to DeLanda, these two terms refer to two entirely different ontological structures. As Harman (2008) explains:

> A species is always made up of individuals (as Darwin observed) and never transcends those individuals to become a permanent natural archetype. By contrast, DeLanda holds that the genus has a virtual structure referring to topological ‘degrees of freedom’ deployed by different species in different ways, and hence the genus must transcend individuals.

According to DeLanda (2011), the reasoning behind this is that assemblages among each other cannot sufficiently account for why *similar* assemblages keep arising, and so having replaced species with assemblages, genera need to be replaced by something else – ‘diagrams’ of ‘universal singularities’ shared by many assemblages, what in DeLanda (2013) is referred to as a ‘structure that determines the space of possibilities associated with a specific assemblage’.

According to Kleinherenbrink (2019), this attempt by Delanda to explain that 'the being of assemblages is not just determined by their private capacities and their local encounters, but also by larger virtual structures ranging over entire populations of similar entities,' leads to the construction of a 'cosmic plane' in which these diagrams operate, which he feels makes DeLanda's supposition feel 'like a Neoplatonic theory in which entities emanate from a cosmic height'. This indeed does seem like a convoluted way to eliminate genera. Not without critical glee, Kleinherenbrink (2019) goes on to recall that

> DeLanda already thinks that assemblages form other assemblages. […] Why on earth would we then need to add diagrams to account for similarity? If I cook the same three meals every week, is that not perfectly explainable in terms of specific machines (myself, the supermarket, my kitchen, recipes I know, and so on)?

AAA sides with Kleinherenbrink to challenge DeLanda's three basic constituents – assemblages, diagrams, and the cosmic plane – by stating that only definitions are needed, but that those definitions can exist in different *modes* (exercising different capacities). Morphogenesis takes place in a definition that is in the multiplicity mode, while identity maintenance takes place in one existing in the assemblage mode. As we are always dealing with 'assemblages of assemblages,' a definition may of course be in several modes at the same time. No matter which mode or modes it is in, the definition always has a virtual structure referring to topological degrees of freedom.

DeLanda (2006) points out that such topological constraints are 'not actual but virtual and mechanism-independent, capable of being realized in a variety of actual mechanisms'. In other words, rather than being causal, they are – to use Deleuze's term – quasi-causal. Such quasi-causes rival the mechanistic theory of linear causation, which assumes that the same causes always yield the same effects. The most notable additional rival to linear causation mentioned by DeLanda is catalysis. The main difference between the two is that quasi-causes are virtual and catalyses actual. An assemblage's catalytic ability belongs to it as a capacity, and both types of causation are productive, in that, as Harman (2008) puts it, 'there is always more in the effect than there was in the cause'.

v) Form follows fitness: Schema

The two mechanisms that give birth to and maintain space can be viewed as a mirroring of the meta-heuristic processes – evolutionary solving that produces symmetry-breaking cascades – that makes form follow fitness within AAA definitions. With minor variations, the schema aligns with the following pattern:

The production of space begins with a definition in the multiplicity mode. This multiplicity is composed of the form seed and its parametric domains, but also the different parameters (flows of data) that can influence the form seed, as well as the evolutionary solver and genetic algorithm used, the objectives and constraints within the definition (together with their associated data), the contextual situation (including but not limited to the project's environment), and so on. It is a *structured* space (it structures a space of possibilities) but not yet an *arranged* (ordered, selected) space.

‘Switching’ to the assemblage mode, the *arranging* of this space begins as differences in parametric in data – potentially including anticipatory information – are repeatedly fed to the form seed in order to instantiate new individuals from the virtual design space demarcated by the definition’s multiplicity mode. The ontological status of this instantiated level can be viewed as being positioned in between the virtual and the actual. Instantiated solutions, in other words, are the phenotypes actually explored by the evolutionary solver, the data points that can be accurately mapped in a model of the design space.

The adaptive mechanisms of the evolutionary solver are used to move the system towards a predefined ideal set of phenotype targets. A variety of analysis methods and search strategies are employed to select a final individual to be actualised.

While the maintenance of this individual is perhaps harder to grasp intuitively, the use of sliders to control its geometry makes the mechanism quite explicit. As long as the slider settings that produce the geometry are preserved, the geometry stays the same, but the slightest change in settings will introduce a difference, effectively turning it into another individual.

vi) External relations

Next, following Deleuze (1953), AAA holds that ‘relations are external to terms’. We must not undermine or overmine (fall prey to microreduction or macroreduction of) reality. Again, Kleinherenbrink (2019) expertly dismantles the original statement and provides an explanation that is worth quoting at length:

> A term can be anything: a tornado, a truck, a game of tennis, a pang of fear, or a tomato. It does not need to be human or even alive. Relations include but are not limited to touching, seeing, colliding, pulling, having, knowing, crushing, seducing, rubbing, placing, containing, destroying, and creating. Externality means that an entity in itself is never present in its relations. It posits a difference in kind between an entity itself and its manifestations, which makes direct contact between entities impossible (as an entity can only ever encounter other manifestations, not other entities as such). It implies that each entity has properties constituting an excess over and above its current, past, future, and even possible relations. This is the case even if it exists for a mere second, during which it is at the complete mercy of other forces. Even in the most smooth-running machine imaginable, all parts will thus remain ontologically irreducible to that machine as well as to each other. There are such machines all the way to infinity: ‘each segment is a machine or a piece of the machine, but the machine cannot be dismantled without each of its contiguous pieces forming a machine in turn, taking up more and more place’. In short, externality means that nothing is reducible to anything else, even if ‘anything else’ is everything else. […] externality also does not lead to an old-fashioned dualism that divides reality into ‘relational stuff’ and ‘term stuff’. Externality merely states that entities are not exhausted by their relations, whether they be atoms in a molecule or notes in a symphony.

This 'excess' points to a certain redundancy: since in AAA realism, no entity can ever be reduced to its relations with other beings, nor to their parts and environments, and since the ontological status of any assemblage is what DeLanda (2006) calls 'that of a unique, singular, historically contingent individual,' an assemblage (definition) does not necessarily require all components that currently contribute to its (re)production.

vii) Dispositions

Over and above properties, a AAA definition has certain 'dispositions' – its associated tendencies and capacities. While fully real, these need not be actualised at any given moment. The actualisation of properties depends on these dispositions. As DeLanda (2016) puts it,

> assemblages are characterised by enduring states defined by properties that are always actual, existing in the here and now. But in addition to properties, assemblages also possess dispositions, tendencies and capacities that are virtual (real but not actual) when not being currently manifested or exercised. Moreover, when the concept of assemblage is endowed with parameters, the zones of intensity defined by the latter, and the critical values of the parameters mediating between zones, have the same ontological status as dispositions.

AAA assemblages (definitions in the assemblage mode) are always endowed with parameters. When the combined settings of those parameters happen to cross a critical value, the assemblage undergoes a transition: it changes state to generate a new geometry with associated out data. *Tendencies* allow an assemblage to change what it is already doing: increase filleting to transition from box to sphere. *Capacities* allow an assemblage to accomplish an entirely new actualisation: become a Lego helicopter instead of a Lego car.

viii) Multifold structures

In DeLanda (2013, 2016), the virtual capacities of an assemblage are said to define its 'possibility space'. This is synonymous with 'design space' in AAA, and with the fitness landscapes first described in Wright (1932). Recall the sliders we added to our sphere-box experiment above. We noted then that the actualisation of one of DeLanda's assemblages coincides with its positioning along two main axes, which are crossed to produce a fourfold structure of the world: the first axis, or dimension, defined a gradient from the purely material to the purely expressive; the second dimension a dualism stretching from territorialisation (a stabilisation of the assemblage's identity) to deterritorialisation (a destabilisation of the assemblage's identity).

Ever the attentive critic, Harman (2008) points to the fact that for both those dimensions, 'what allows an assemblage to flip back and forth between material and expressive, or territorializing and deterritorializing, are its capacities rather than its properties'. 'In a sense,' writes Harman,

> that is how all populations generate new assemblages, by turning their formerly expressive dimension into the raw material for a new assemblage that uses only a

> subset of the population. The accident that some humans of each nation are more interested than others in chess gives rise to international chess league assemblages.

Harman's objection to what he calls 'DeLanda's refreshing and marvelous ontology' is that what an assemblage's properties are is never fully developed, but defined in terms of its capacities to affect and be affected by other things. AAA addresses this (valid) objection head on, by always mapping properties as out data (corresponding to predetermined objectives) for each instantiated or actualised individual. AAA keeps track of all properties.

However, it is important to note that AAA also questions the highly simplified fourfold structure that DeLanda proposes (and to an extent inherits from Deleuze and Guattari), which, as we saw, is composed of two sets of parameters deemed to be necessary to define the structure of an assemblage. These fourfolds lead to a pluralist ontology in which each entity is irreducible because of the absolute discontinuity that exists between entities – but why stop at the crossing of *two* axes? We outlined above how the structure of AAA's is fundamentally based on 'two double articulations within a double articulation,' but the parameters, objectives, and constraints that define the AAA can in theory hold as many dimensions as the available resources (time and computing power) allow for. Assemblages are characterised by emergent properties that cannot be found in their components. An instantiation of the box-sphere has a volume that is different from that of the box and the sphere separately, and certainly different from the value of the parameter that controls its relative degree of filleting. The structure of AAAs are of a multifold nature, suspended between many coexisting dimensions, producing and maintaining wholes that are always more than the sum of their parts.

Let us conclude this chapter by summarising the mechanisms and key terms. Such a summary demands a few new interpretations that we shall return to in due course below. Everything that exists is viewed as being simultaneously a definition and an assemblage. An *assemblage* is an arrangement through extrinsic relationships of heterogenous historical parts into emergent compositions. A *definition* is everything that an assemblage is, but also a map or diagram of its mechanisms, the possibility of making it repeatable. They are also AAA's way of further flattening DeLanda's 'flat ontology': everything is a definition, but definitions can function in different modes (exercise different capacities) depending on the context (similar to how a knife may be a bread-cutting device or a murder weapon).

The realist AAA ontology is based on two *double articulations* nested within a larger double articulation. The latter divides space into being either born or maintained. Such spaces can be virtual or actual, either way they are always real. *Morphogenesis* (the generation of form) begins with a definition in the multiplicity mode. *Multiplicity* is a term for the entire space of possibilities available in the world, the *design space* of the universe. Space is born as this definition uses its internal *constraints* (its limitations or restrictions) to structure a part of the multiplicity (adjust its intnernal singularities), similar to how the mountain in our example above structured the flow of the river. This produces *virtual* (real but not actual) geometries through historical-genetic processes ('paths through the maze' of the design space).

Adaptation is the process of change by which a geometry becomes better suited to its context. *Anticipation* occurs when a dynamic system is capable of running faster than the dynamic system it is a model of, that is, faster than real time, which renders it capable of predicting (to some non-perfect accuracy) future behaviour. Space is maintained (spaces retain their identity) by a combination of intrinsic adaptation of the space to its own capacities and extrinsic anticipation of its future possibilities.

The AAA process ‘hacks into’ the ontology above through a sort of biomimicry-without-the-mimicry, that is, by creating a form-producing system that employs similar processes as those producing natural forms in the world. This begins with the creation of a particular kind of definition called a *form seed:* a parametric geometry (an assemblage) that can accept quantified input data (values) as parameters capable of calibrating the geometry. Evolutionary solvers running genetic algorithms are employed to adapt those geometries *(phenotypes)* to their context while keeping track of the anticipatory outcomes (output data) of each new assemblage produced. Producing a final form is equal to optimising the settings of the input parameters to yield the best-possible output data.

METHODOLOGY

5. METHODOLOGY

Why do architects and engineers need a methodology? Because it endows our ontological structure (our understanding of the inner workings of the universe, which for the present study translates as the assemblage mechanisms described in the previous chapter) with an *agency* (the capacity to influence the world and create desired futures). In short, to translate a cogent theoretical framework into actualised structures, architects and engineers need to know what to do and how to do it. Designing a methodology is a way of bridging the gap between our limited understanding of the world and our desire to remodel that world.

Arguably, in order to design something, one first needs to design the method for designing that something. As Sagan (1980) wryly noted, if you 'wish to make an apple pie from scratch, you must first invent the universe'. As designers of desired futures (apple pies), architects and engineers furnish (invent) environments (universes) in which such futures may be designed. If the underlying axiology (further described in chapter 5 below) provides a reason and a rationale for remodelling the world, and the ontology contributes the working material as an understanding of the medium to be remodelled, then the methodology supplies the overarching strategy and working methods necessary to change the structure and/or form of the material in the light of the rationale.

The methods we design inevitably connect the future to the past. Sagan (1980) goes on to note that our achievements 'rest on the accomplishments of 40,000 generations of our human predecessors, all but a tiny fraction of whom are nameless and forgotten'. This may be so, but consigned to oblivion or not, their attainments, over time, formed bodies of theoretical and empirical knowledge that we now acknowledge as individual disciplines. Every discipline once inherited and now employs a body of methods, rules, and postulates, particular procedures or sets of operations recognised by practitioners as valid strategies for achieving preferable outcomes.

Some disciplines utilise a smaller set of operations than others. There are many recipes for apple pies, but most of them involve the heating of apples (and often wheat) in an oven. Likewise, structural engineering employs a set of trusted equations that rarely change. But while Plowright (2014) summarily divides the development of architectural form into three major methodical frameworks based on patterns, concepts, and forces, respectively, architectural methodology is a highly heterogenous and diversified field. As noted in Jormakka (2013), contemporary architectural practice involves for instance mimetic (imitative) methods such as Frank Gehry's folding of sketch models made out of torn paper (Goldberger 2015) and Frei Otto's translation of soap bubbles into built structures (Songel 2010); diagrammatic methods such as those represented in the work of Peter Eisenman, Bernard Tschumi, and UN Studio, or the earlier proportion studies of Le Corbusier or Palladio, for good overviews, see Garcia (2010) and Chaplin (2014); and heavily computer-dependent parametric methods such as the 1995 design of the Yokohama Ferry Terminal by Foreign Office Architects (Kubo 2002) and the entire oeuvre of the late Zaha Hadid (Jodidio 2020).

Constructed as a highly dynamic framework, AAA has the capacity to embrace all of those modi operandi and more within its methodological structure, which is, however, firmly situated in the latter (computer-based and parametric) faction. The rest of this chapter provides a clarification of the fundamental concepts and mechanisms underlying the AAA methodology, together with an accessible introduction to the core procedures underlying the production of AAAs (including a visual step-by-step guide in section 5.2), ending with a brief interrogation of how the notion of experimentation in architecture can be more warranted when designing AAAs than when not.

5.1 Both/and: The methodological design of AAA

While French phenomenologist philosopher Gaston Bachelard had nothing like this in mind when he wrote, in Bachelard (1958), that there exists 'a dynamic rivalry between house and universe' and that 'the house is an instrument with which to confront the cosmos,' his simultaneously accurate and hyperbolic remarks might be a helpful starting point from which to explain the AAA method, which *anticipates* forces from the context ('the universe') to produce an *assemblage* (a building, or 'house') that *adapts* to its environment (confronts 'the cosmos').

Achieving this anticipatory adaptive assemblage is a perilous balancing act, a matter of negotiating and accommodating a range of typically opposing forces interior and exterior to the project its geometrical definition encompasses. Before the introduction of powerful computers and advanced software, it was for practical reasons impossible or very cumbersome indeed to simultaneously incorporate even a limited number of such forces in a quantifiable design process: more often than not, the trade-off between the value of that gorgeous view of the lake and the cost of those larger windows came down to an emotional negotiation between architect and client. The AAA methodology rephrases the argument as a mathematical analysis: given a site and a budget, a discrete number of design options exist that make the windows as large as they can be without breaking the budget. Allowing several such opposing desires (the maximisation of window size vs the minimisation of cost) to simultaneously inform a design is what AAA does. The mathematical term for such analyses is *optimisation*.

As Eiben & Smith (2015) note, in a mathematical optimisation problem, 'the model is known, together with the desired output (or a description of the desired output), and the task is to find the input(s) leading to this output'. When two or more such objectives are pitted against each other, a design can become a series of 'optimal compromises,' exploring the fertile common ground in between the extreme positions. Metaphorically, the 'either/or' attitude of, say, hardcore political absolutism is replaced by the 'both/and' reaction of elements present for instance in chemical diffusion. This methodological shift turns architecture into a realm capable of accommodating a wide array of diverse sustainability prospects and metrics: the life-cycle assessments of building materials *and* the conservation of building energy, commercial potential *and* reasonable carbon footprint, structural integrity *and* aesthetic impact, and so on.

The promises and challenges particular to the multifaceted area of architecture thus by definition lend themselves to becoming part of *multi-objective optimisation* strategies: a mathematical field in which more than one objective function is optimised simultaneously. This shouldn't really come as a surprise. As Wortmann & Nannicini (2017) point out, optimisation is a fundamental aspect of the design process. Designers always seek to accommodate conflicting desires, be they the careful implementation of classical orders on a difficult site in the times of Vitruvius, or the maximisation of floor space within the confines of contemporary building regulations today. As noted in Larsson (2014), architecture is always a result of negotiated conflicts and compromises. Importantly, the outcome of the AAA process is usually a (typically very high) number of design iterations that answer more or less well to the different combinations of objectives within the stipulated constraints, and not rarely a number of iterations with identical performance metrics but different geometries. Finding alternative effective strategies for managing such situations is an important part of the future development of the AAA methodology.

In Walliman & Walliman (2011), research is defined as 'an activity that involves finding out, in a more or less systematic way, things you did not know'. O'Leary (2004) distinguishes four key elements that allows the researcher to find out such things: 1) *methodology* is 'the framework associated with a particular set of paradigmatic assumptions' used to conduct research, 2) *method* is the techniques used to produce the research, 3) *tools* are the devices employed to reach the goals, while all of the above together make up 4) a 'methodological design' – the plan for conducting the study. In AAA, the methodology is multi-objective optimisation strategies, the method is meta-heuristics, and the tools are parametric systems that employ strategies (algorithms, simulations, and so on) from the fields of computational design and artificial intelligence. While the methodological design can be tweaked to cater to almost any objective, it typically involves a highly site-specific response to the local environment (including its weather) and a certain sensitivity to the 'auxiliary loads' of building materials. While this methodological design is present in all papers, the latter typical objectives are particularly well accounted for in Paper IV and Paper V.

The primary meta-heuristic vehicles used to carry out multi-objective optimisation strategies in AAA are evolutionary solvers and genetic algorithms. These were popularised in the mid-1960s with Lawrence J. Fogel's landmark doctoral dissertation *On the Organization of Intellect* (Fogel 1964), which sparked the first endeavours into evolutionary computing. The emergence of a new digital tectonics in the early 1990s provided architecture with the tools necessary to allow designers to align with this trajectory by effectively using the computer, as Frazer (1995) puts it, 'not as an aid to design in the usual sense, but as an evolutionary accelerator and a generative force'. About ten years ago, David Rutten's implementation of the evolutionary solver Galapagos within the Grasshopper 3D environment made it relatively easy to utilise genetic algorithms within an architectural design methodology, initiating a massive surge in the number of research agendas devoted to and papers written on the topic. As touched upon in Paper V, the number of actually constructed projects based on evolutionary optimisation is decidedly lower.

The above reasoning may at first sound very abstract, but it has highly pragmatic consequences for how we can plan, arrange, and build our physical environments. In particular, enhancing architectural and engineering designs using genetic algorithms tackles what Rittel & Webber (1973) call the 'wicked problem' of how to compute the contextual inputs of a scheme by allowing data flows and 'invisible' strategies such as material life-cycle analyses, advanced weather simulations, and artistic agendas to influence the process in ways that challenge the traditional primacy of built form.

The AAA method allows us to digitally design 'evolutionary architecture' using generative forces provided by genetic algorithms. While this field is still nascent, and while no consensus exists that establishes one method's superiority with regards to the production of architectural form, the method employed by this author to design AAA architecture follows a simple schema: A *form seed* is developed in Grasshopper. This is a (virtual) parametric 3D model with input parameters (typically fed to the model as numerical slider values). The form seed is an assemblage (in biological terms a *genome)* that, as its input parameters are changed, produces a *difference* that is then recorded as a (digitally actualised) geometry *(phenotype),* which in turn carries output data. The form seed exists under the pressure of various environmental and contextual conditions defined by constraining parameters to which it is forced to adhere. The output data is typically the result of simulating the performance of the geometry when exposed to some condition, an operation that uses *anticipation* – a prediction of performance – to produce *adaptation* – an optimisation of performance.

To exemplify, the environment might be a combination of a particular site (the Bronx Zoo in New York), a particular brief (maximise floor space, minimise CO_2 footprint and cost, and provide as good views of the giraffes as possible), and a particular budget (typically small). The form seed might be a vertically elongated box, the top of which may be rotated to produce a twisted tower. The input parameters could then be the dimensions that govern the tower's length, width, and height, and the rotation angle of its top surface. The output data could be floor area, amount of CO_2 emitted as embodied energy (predominantly from building materials) and operational energy (used for instance to heat and light the giraffe tower), total cost, and window area facing the giraffes. Using an evolutionary solver, we could now instruct the computer to test different input parameters for the form seed, thus producing (many) populations of phenotypes, and then compare the output data to assess which iteration produced the best possible compromise between our goals. This would be a AAA response to the design brief.

5.2 The Octoscraper: An example

Let us illustrate the methodology further using a visual example. Following a typical (if ideal) progression of the genesis of a AAA project, we shall construct a concept, design a form seed (an assemblage) that corresponds to that concept, optimise the form seed by providing anticipatory and adaptive mechanisms in the form of a solar radiation study and an evolutionary solver (respectively), and actualise the resulting final geometry as a photo-realistic render of the scheme (the next-best option to actually constructing the building, which, sadly, our resources do not stretch to).

One (simple) way of creating an architectural concept is to merge two precedent studies and see what comes out of the forced juxtaposition between the schemes. For the present exercise, the white enamel panel grid reoccurring throughout Richard Meier's oeuvre and the brutal lattice façade of Steven Holl's sponge-like Simmons Hall building were amalgamated into an idea of a tall building recursively subdivided into repetitive gridded boxes that nevertheless retain a measure of adaptation in that the width of the 'grid lines' (that is, the frame-versus-glazing ratio) changes in accordance with the underlying façade's exposure to solar radiation, a metric that simultaneously drives the process of optimising the building geometry so as to maximise building volume and the amount of solar radiation falling on its façades while minimising its footprint.

Precedents and octress

Throughout Richard Meier's stormy career (the zenith of which was arguably his being awarded the Pritzker Prize in 1984, its nadir opposite the sexual harassment allegations in 2018 that led to his resignation from the firm he opened in 1963), the modernist architect has perfected a neo-Purist typological design agenda – it has often been suggested that he has built more using Corbusier's ideas than anyone, including Le Corbusier himself – that merges strict adherence to an orthogonal grid with a remarkably constricted and pristine material palette that imparts a crisp geometric whiteness to his architecture. While designed by the world's foremost neo-modernist architect, Meier's buildings remain, according to the Encyclopedia Britannica (2020), 'refinements of and variations on classic Modernist principles: pure geometry, open space, and an emphasis on light'. While in some buildings, such as the 2008 ECM City Tower in Prague, the grid is selectively perforated so as to suggest site-specific adaptation, this variation only occurs within the confines of the grid, which is never allowed to differ dimensionally.

Figure 13: Richard Meier's ECM City Tower in Prague and Steven Holl's Simmons Hall on the MIT campus. (Richard Meier Architects; Steven Holl Architects)

Steven Holl's 2002 Simmons Hall at the MIT is a ten-story dormitory housing some 350 undergraduates and including additional features such as a 125-seat theatre spanning two storeys, a night cafe, and street-level dining. In Holl (2000), the architect rhetorically asks 'what if one aspect of a site – porosity – becomes a concept?'. This is of course precisely what happens in this building, formally reminiscent of the pixelated alien graphics known from Tomohiro Nishikado's classic arcade game, Space Invaders, which according to Hansen (2016) 'invaded the allowance of every kid tall enough to see the screen' upon its release in the summer of 1978. The sponge-like structure is a study in contrast: solid and void, opacity and transparency. Its 450mm deep walls allow the low-angled winter sun to heat the rooms, while shading the building in summer. But as with Meier's building, there is no dimensional difference in the repetitive window grid, no site-specific adaptation in the filtering of light into the individual spaces behind the porous façade. The precedent buildings by Meier and Holl are shown in Figure 13.

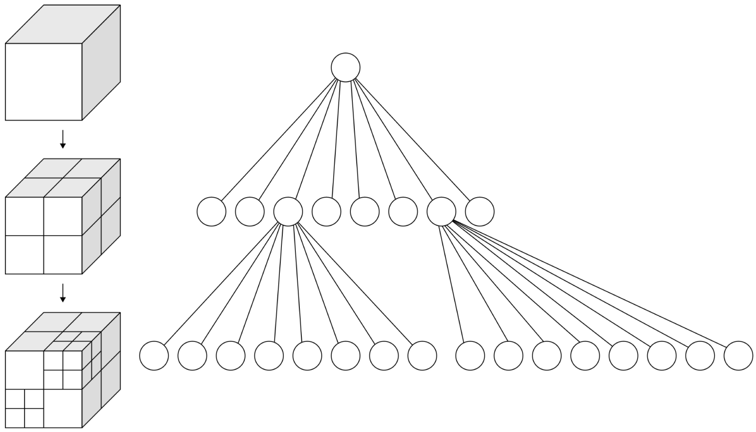


Figure 14: The recursive octree principle partition a three-dimensional space by recursively subdividing it into eight octants, that is, it is a tree data structure in which each internal node has exactly eight children. (White Timberwolf/Wikipedia)

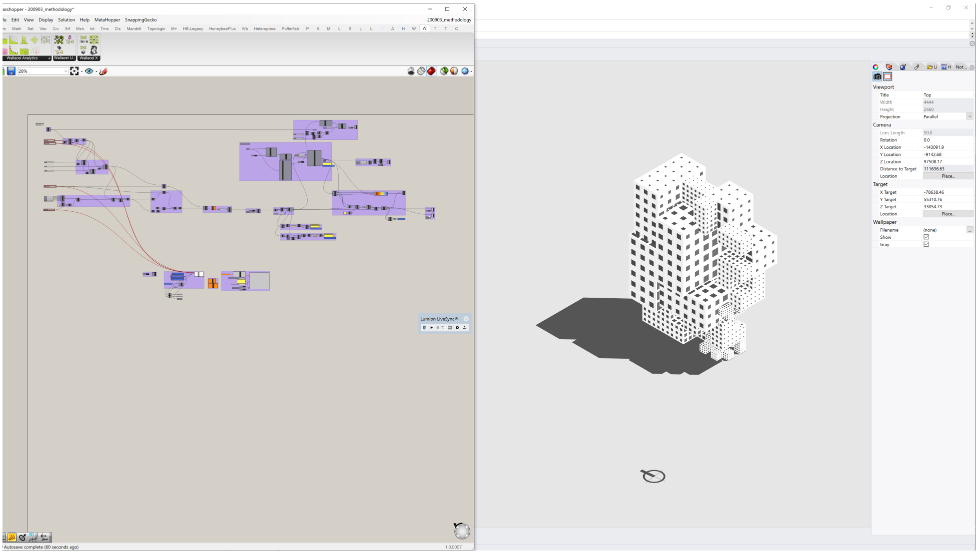
Designing the Octoscraper: A visual guide

The following visual guide provides a step-by-step account of the visual (Grasshopper) programming that goes into the creation of the Octoscraper example, that is, the procedure behind the creation of an anticipatory adaptive assemblage.

The form seed used is an octree structure. The octree principle is shown in Figure 14 – a three-dimensional representation of a tree data structure in which each internal node has exactly eight children, used to partition a three-dimensional space by recursively subdividing it into eight octants. This octree geometry is further described in Meagher (1980). An overview of the definition and its resulting geometry is shown in image 01. The design of the form seed is shown in images 02–11. A simple solar radiation analysis using the Ladybug plug-in for Grasshopper described in Roudsari & Pak (2013) is shown in images 12–15. The results are used to cull boxes from the octree geometry. Exploring the well-known dichotomy between beneficial winter sun and detrimental summer sun, the definition adjusts window sizes accordingly. Using the Wallacei evolutionary solver, configurations are produced that optimise the geometry, as shown in images 16-18 (for instance minimising the footprint while maximising the solar radiation falling on the façade surfaces). Image 19, while image 20 shows the resulting geometry photo-realistically illustrated as a digital rendering.

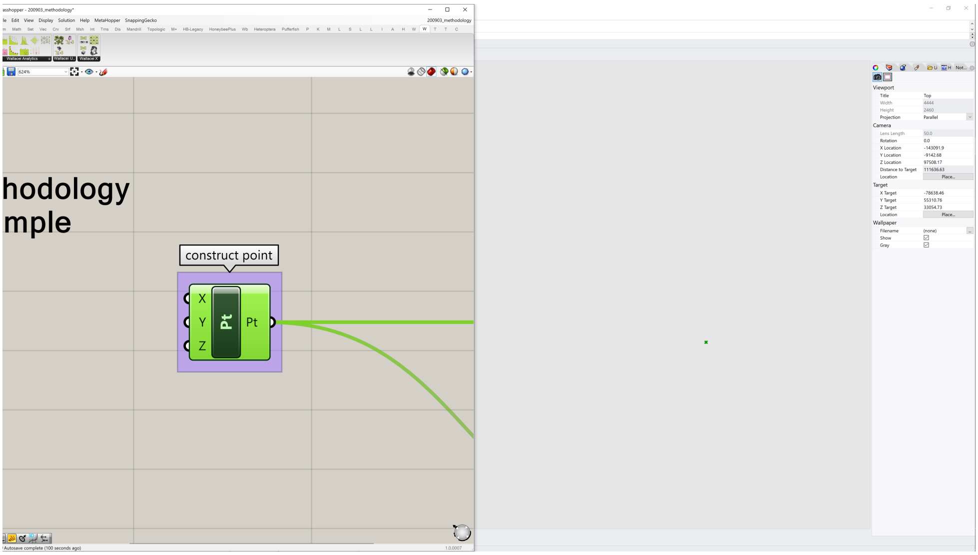
01

The end result. An overview of the entire definition and one of its resulting geometries.



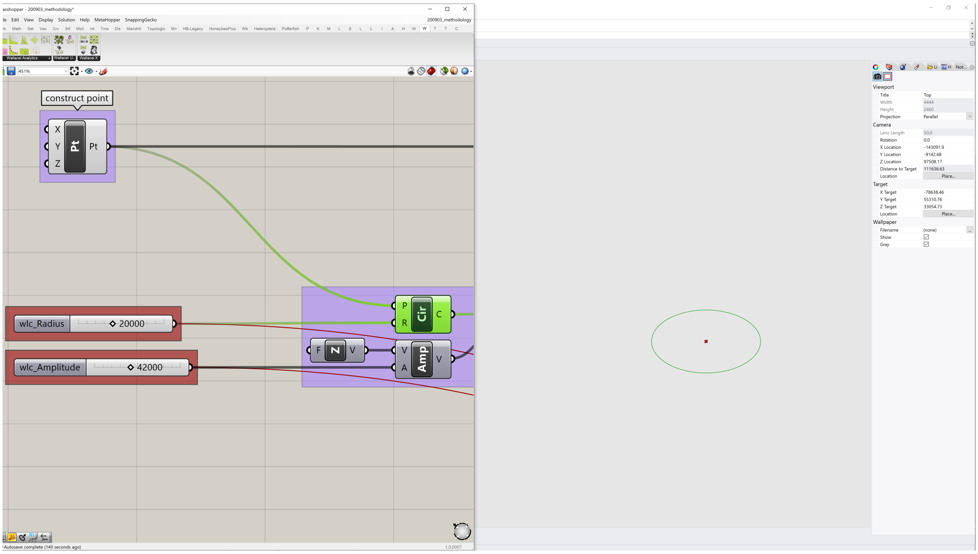
02

Construct a POINT on the GROUND (xy) PLANE, corresponding to the site coordinates.



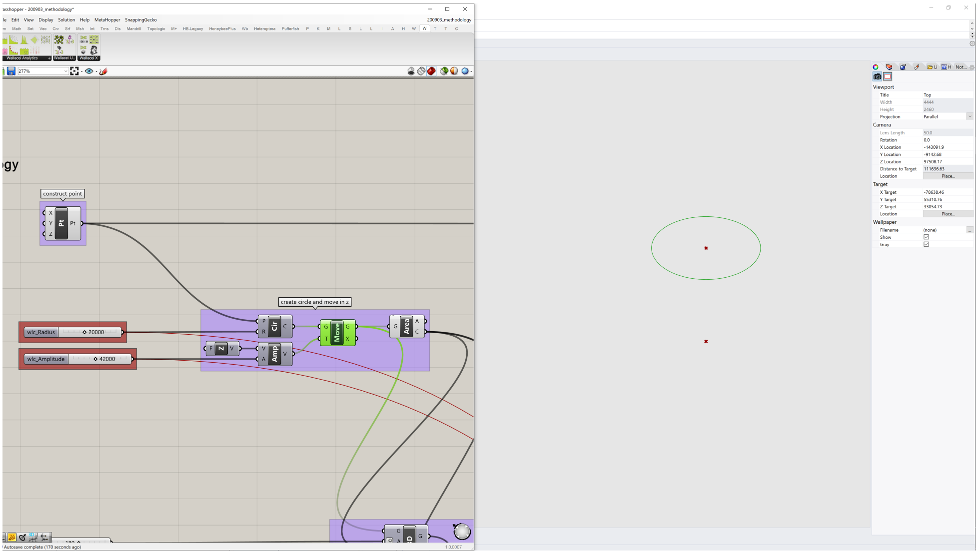
03

Construct a CIRCLE, with a parametric RADIUS, using the initial point as centre point.



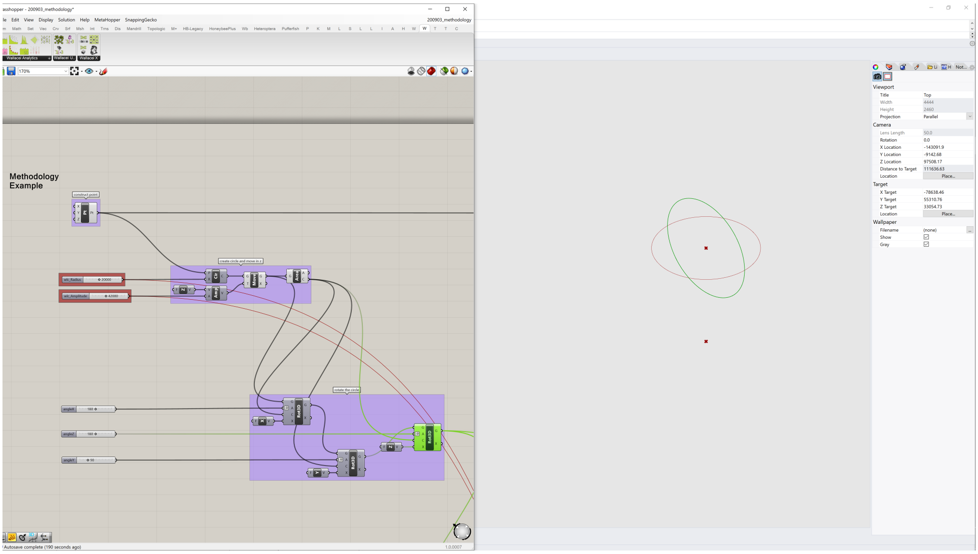
04

MOVE the circle along a vector in the z direction by a parametric AMPLITUDE (distance). Add the AREA command to retrieve the CENTRE POINT of this second circle.



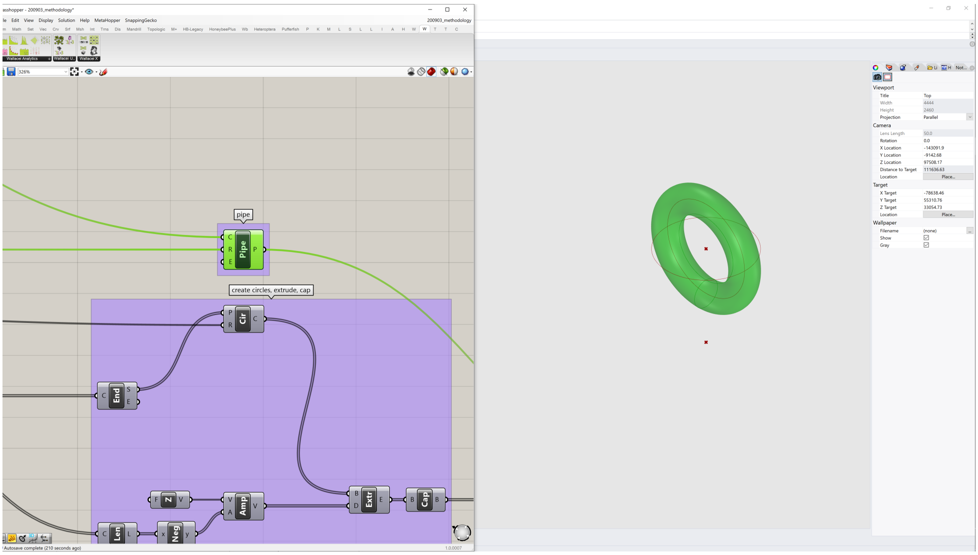
05

ROTATE the circle in three dimensions (x,y,z) about its centre point.



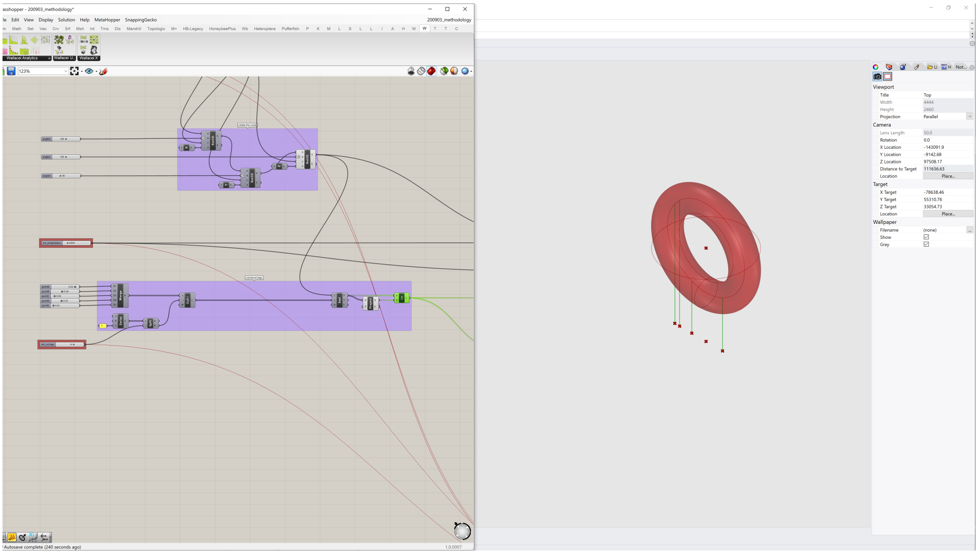
06

PIPE the circle using a parametric RADIUS.



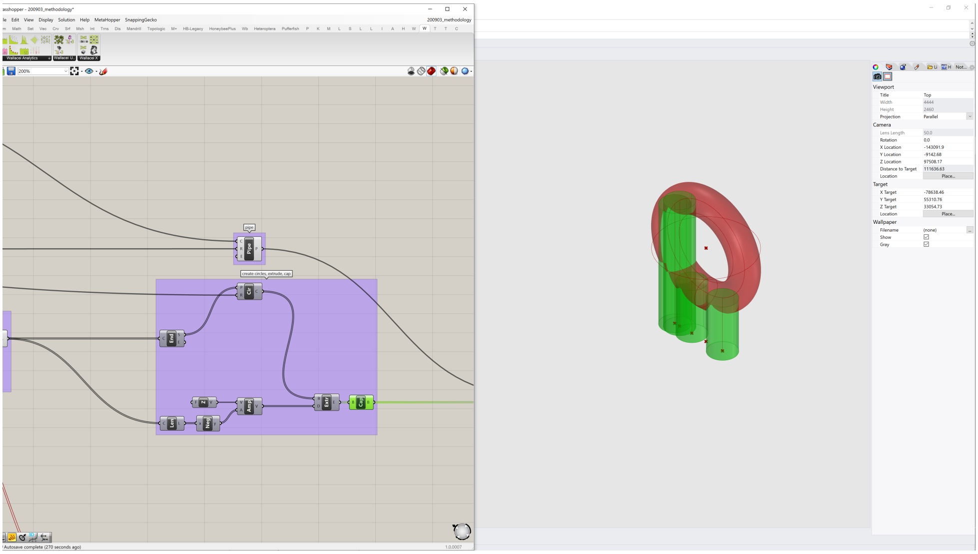
07

Position a parametric number of POINTS on the circle, PROJECT them down to the ground plane, and construct LINES between the initial and the projected points.



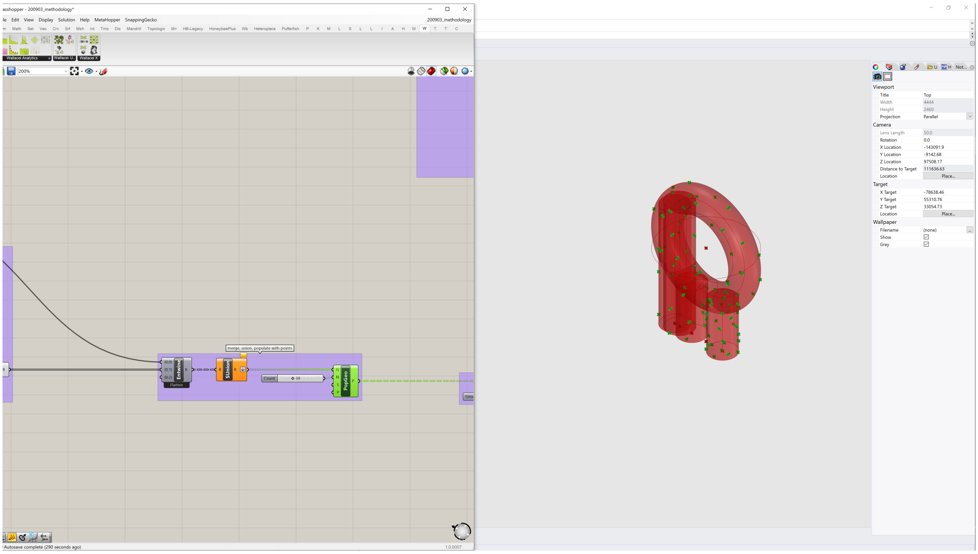
08

Construct CIRCLES about the initial points, with the same RADIUS as the pipe. EXTRUDE these circles along the line to the ground plane, and CAP the resulting CYLINDERS to produce closed BREPS (boundary representations, a computational method for representing shapes using their limits, effectively drawing the boundaries between solid and non-solid elements).



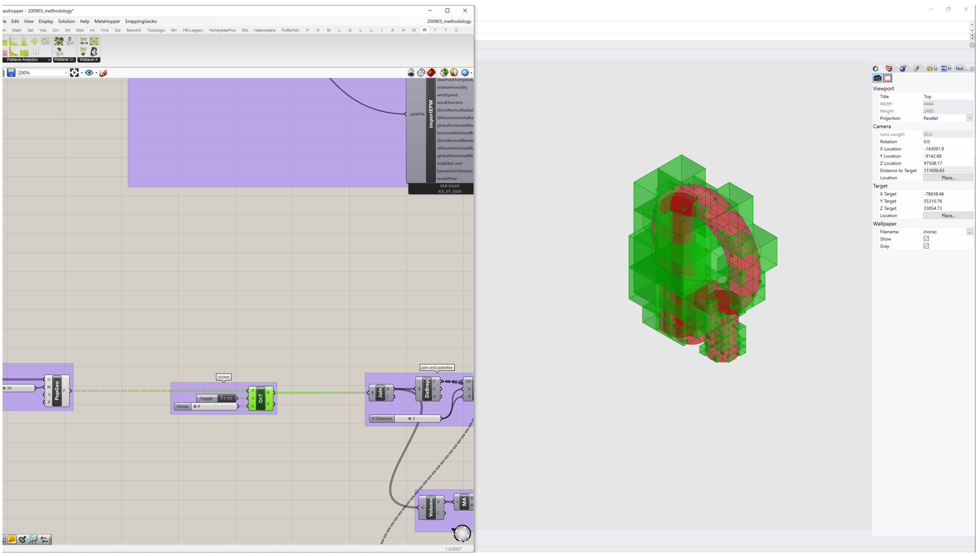
09

ENTWINE and use a SOLID UNION boolean operation to merge the geometry into one. POPULATE this geometry with a parametric number of POINTS (in this case 30).



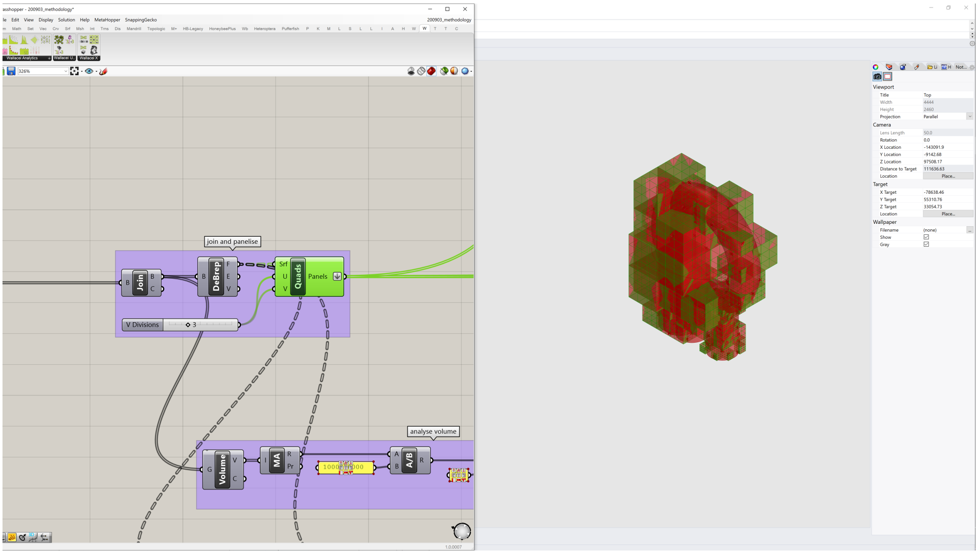
10

Use the OCTREE component to create subdivided BOXES about the points. Use a slider to parametrically control the permitted content per leaf (in this case 0).



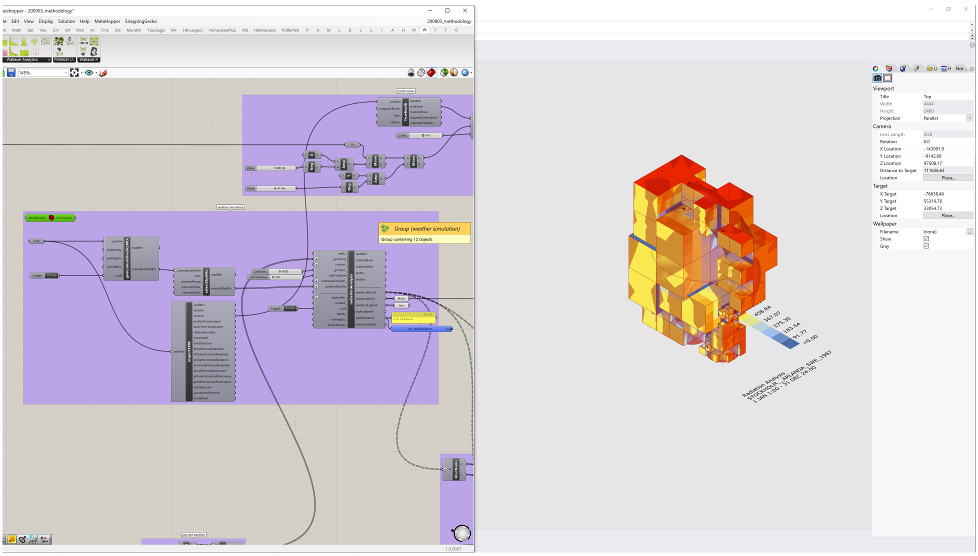
11

JOIN the boxes and subdivide their FACES in the (u,v) directions to add a parametric amount of PANELS to the geometry using the QUADS component from the Lunchbox plug-in.



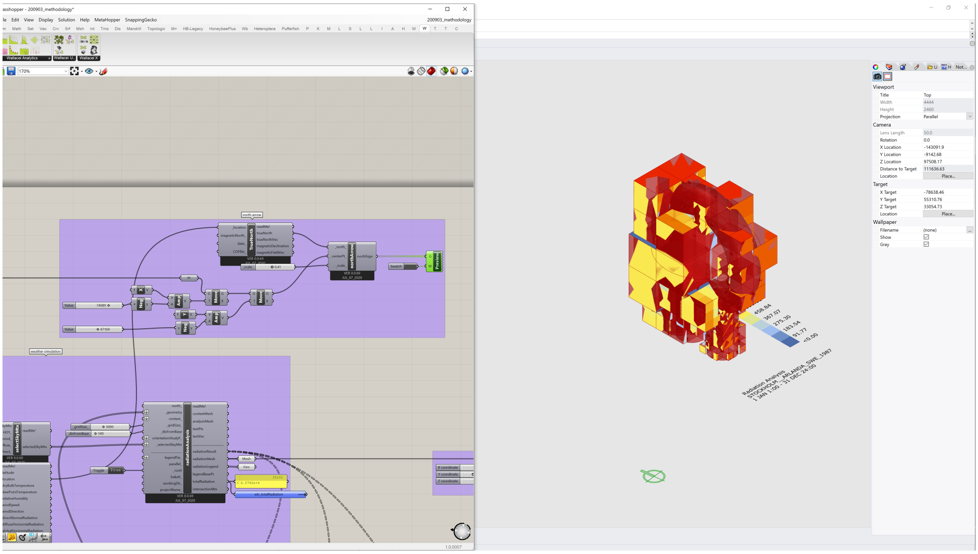
12

Use the Ladybug plug-in to perform a RADIATION ANALYSIS on the panels created, measuring the total annual amount of solar radiation (in kWh/m2) that falls on the structure throughout the year (1 January-31 December).



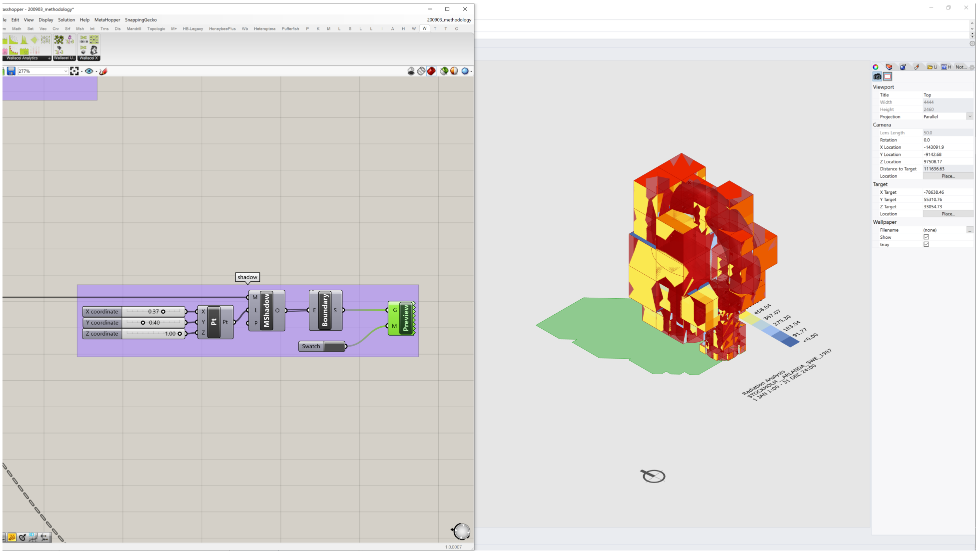
13

Double check that the result in the previous point is reasonable by adding a NORTH ARROW to the scene.



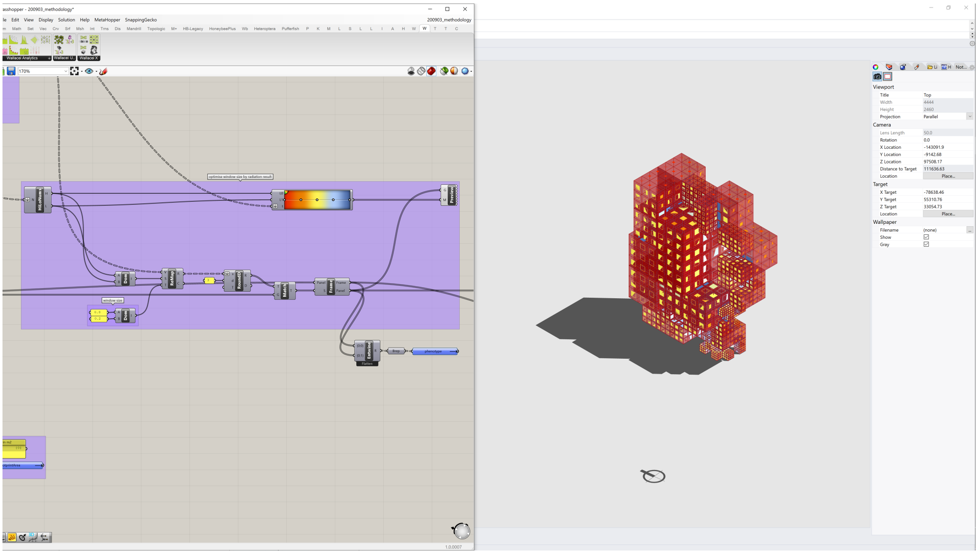
14

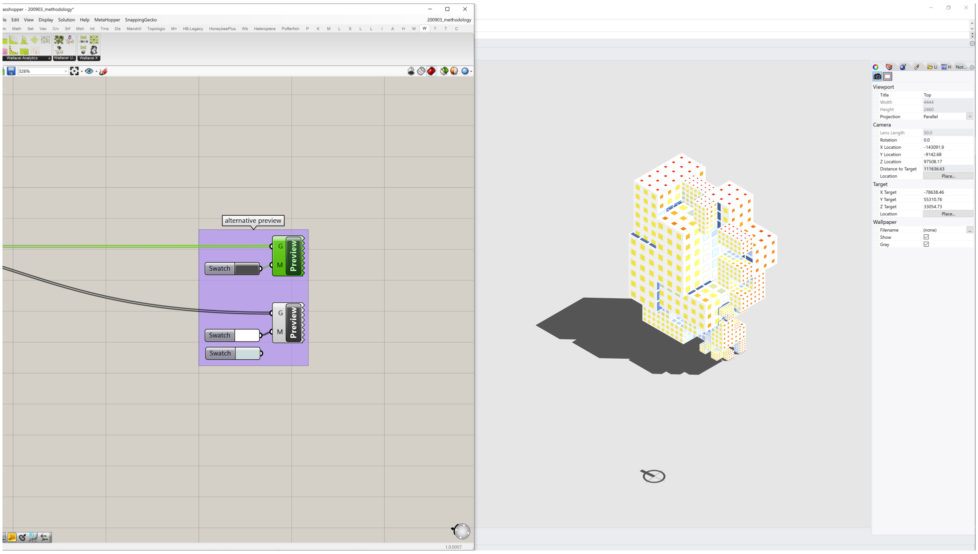
Use the RADIATION MESH to add a SHADOW for illustrative purposes using the MESH SHADOW component (while a 'real' shadow is easily simulated in Grasshopper, this fills no actual purpose in the present example).



15

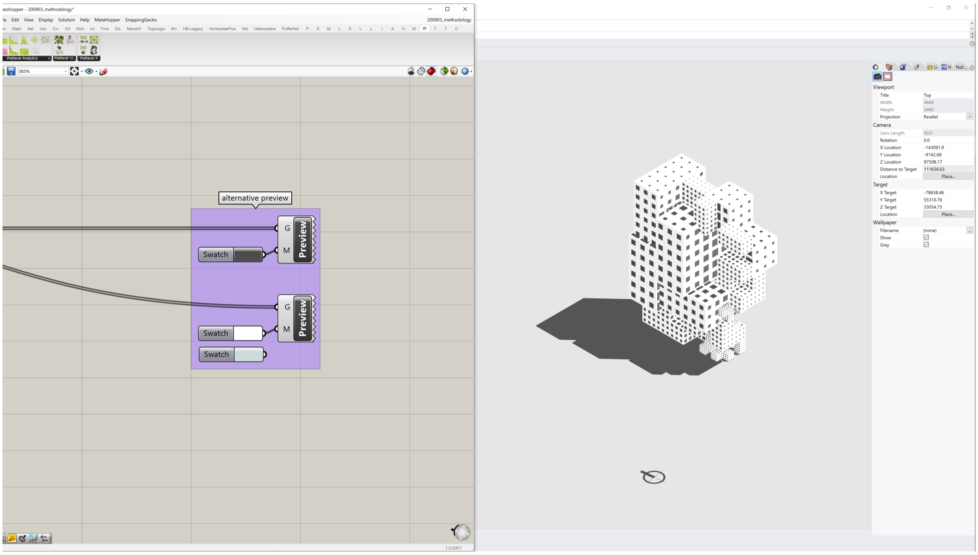
Use the HILONUMS component to construct a DOMAIN from the lowest to the highest amount of radiation falling on the geometry. Use this as the starting domain and REMAP the radiation result values to a new domain, effectively SCALING the building's glazed PANELS (windows) by the amount of solar radiation they receive (the lower the amount of radiation, the larger the window, and vice versa). (ROUND the values and MATCH the lists so that they work with a PANEL FRAME component from the Lunchbox plug-in. This splits the previously constructed quads panels into panels and frames. VISUALISE the relationship between solar radiation and window size by previewing the kWh/m2 gradient across the fenestration.





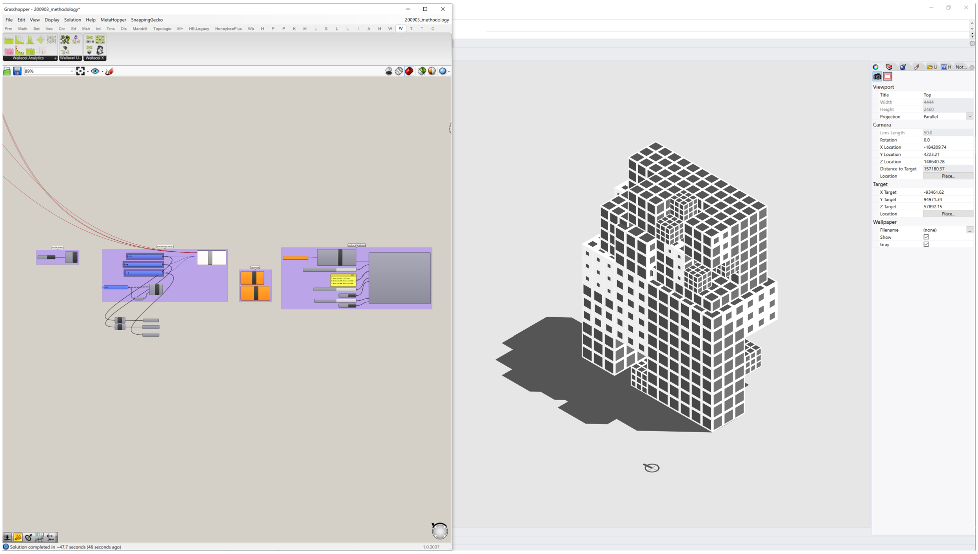
16

Alternatively, for a stark representation similar to that used in the precedent schemes (in particular the sharply delineated drawing style employed by Richard Meier), use preview settings that turn frames white and panels black.



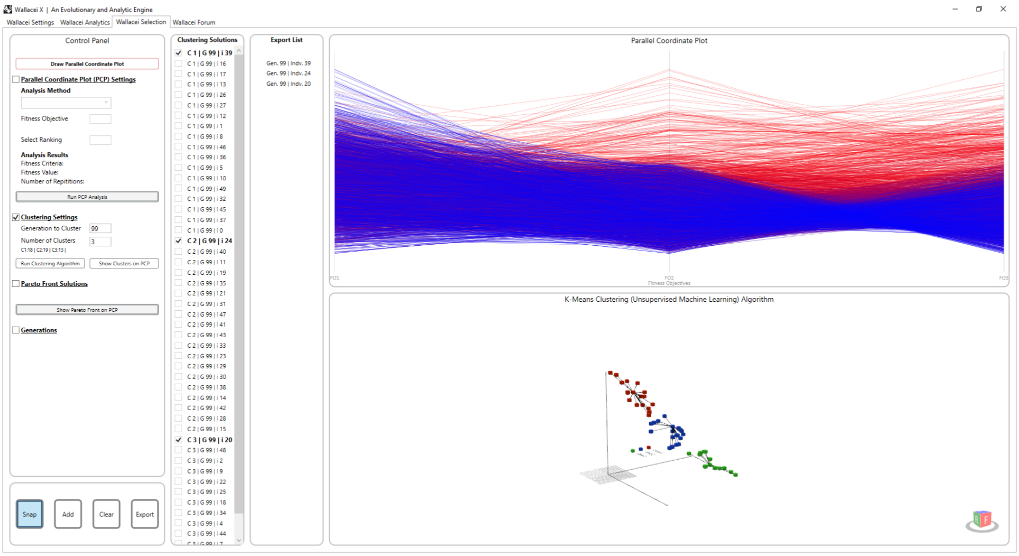
17

Use the WALLACEI plug-in to OPTIMISE the building geometry according to some predefined objectives. This is typically left to run for days to produce optimally performing phenotypes.



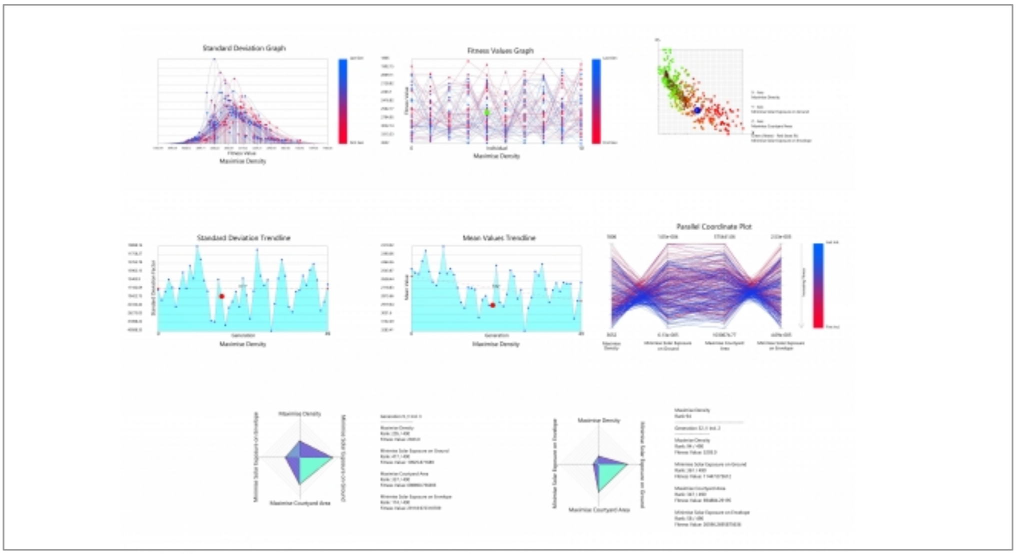
18

Use WALLACEI to selectively EXPORT those generated geometries that perform the best given the predefined objectives.



19

Use WALLACEI ANALYTICS, a collection of analytic charts and graphs o further ANALYSE the assemblages by means of standard deviation graphs, diamond fitness charts, etc.



20

Connect the Grasshopper definition to a rendering software (in this case Lumion) to produce photo-realistic illustrations of the final result.


LUMION
PRO STUDENT

5.3 Artificial and contingent experiments

In his remarkable essay on *The Philosophy of Composition,* Edgar Allen Poe reveals in some detail how the famous poem *The Raven* was composed (Poe 1846). As Jormakka (2013) explains, this 'peep behind the scenes' would make most poets 'positively shudder,' as they are wont to 'pretend that they compose by ecstatic intuition'. Poe's exposition, by contrast, demonstrates that nothing in the poem is 'referable to accident or intuition and that the work proceeded, step by step to its completion, with the precision and strict consequence of a mathematical proof'. Mathematicians reach their proofs through experimentation. While accidents and intuitions are quite compatible with the AAA method, this reference to scientific standards in the world of poetry sets the scene and leads us to consider the the status of the *experiment* in science and architecture. As should be obvious by now, AAA projects by definition *are* the strict consequences of mathematical proofs, but does this mean they constitute *experiments?*

The present thesis argues they do – as opposed to other architectural 'experiments' that *claim* they do. This bold assertion certainly cries out for an elucidation. *A*s Griffith & Brosing (2009) explain, scientific procedures carried out to support, refute, or validate hypotheses always rely on repeatable operations and logical analyses of their results, and as an integral part of the scientific method, the experiment is an empirical procedure that arbitrates competing models or hypotheses while allowing researchers to test existing theories or new hypotheses in order to support or disprove them. This is all quite straightforward as long as we remain in the field of science, but it becomes rather more complicated and less precise when folded into the variegated discipline of architecture. While acts of design typically synthesise an array of intellectual approaches, scientific procedures tend to isolate and refine a single approach – one can 'produce science' by simply observing (and documenting) a phenomenon, but though observing something can certainly be a good starting point for a design, one can hardly 'design architecture' through observation alone. While all experiments are designed, the scientist *crops* a part of the world for study, while the architect *constructs* the object to be studied.

Objects thus constructed using the AAA method are *artificial* and *contingent,* as defined in Simon (1996):

> certain phenomena are 'artificial' in a very specific sense: they are as they are only because of a system's being moulded, by goals or purposes, to the environment in which it lives. If natural phenomena have an air of 'necessity' about them in their subservience to natural law, artificial phenomena have an air of 'contingency' in their malleability by environment.

Simon notes that there exists a historical difficulty in 'filling engineering and other professions with empirical and theoretical substance distinct from the substance of their supporting sciences'. Explaining that fields such as engineering and architecture (as well as medicine, business, and painting) are concerned with design, that is 'not with the necessary but with the contingent, not with how things are but with how they might be,' and that the contingency of such artificial phenomena

> has always created doubts as to whether they fall properly within the compass of science. Sometimes these doubts refer to the goal-directed character of artificial systems and the consequent difficulty of disentangling prescription from description. This seems to me not to be the real difficulty. The genuine problem is to show how empirical propositions can be made at all about systems that, given different circumstances, might be quite other than they are.

This description can be directly applied to the AAA method, which has at least two specific contingencies that make its outcomes problematic as objects of scientific study. Our anticipatory adaptive assemblages are 1) context-driven, and 2) identified as the outcomes of individual historical processes.

Let us begin with the former contingency. While a scientific study of some specimen is typically conducted under controlled and static environmental conditions (for instance at a specific level of temperature and pressure) *in order that it may be reproduced* under the same conditions somewhere else, a AAA project has a highly specific and dynamic set of conditions (such as a geographic location with an ever-changing weather); situating the project somewhere else will drastically change those conditions, and by extension alter the geometries generated by the evolutionary process. A AAA experiment is thus a study of a geometry within a particular context. This can be either a strength or a weakness, depending on the circumstances.

The second contingency above, the unique historical process that produces each assemblage, together with the multi-objective nature of the optimisation processes employed, typically makes it hard to separate and keep track of the controlled, independent, and dependent variables of the experiment. Depending on its design, the often complex nature of the definition of an assemblage can lead to situations in which a change in one parameter calls into action an affine transformation, which in turn activates a different affine transformation, and so on, setting in motion a series of chain reactions that can be very difficult to trace. This means that even though we may be able to record a given variable (in-data) setting and observe a particular outcome (for instance an out-data performance metric), the 'path' within the definition producing the result may still be elusive. Methods can of course be devised to add a higher level of transparency to these mechanisms, and this could be an important area for future studies.

Culley (2016) describes the difficulty of undertaking design research as 'a self-evident truism,' before moving on to declare that it is useful to contrast this approach with the classical scientific method, which he simplifies as

> conceive a hypothesis or generate a theory, in conjunction with undertaking some background contextual investigation or some modelling, construct an experimental approach, perhaps with well-instrumented test rigs and then conduct a series of experiments with a detailed control of key variables and then compare the results with the theory or the analytical models and draw some conclusions. These approaches are recorded, published and crucially are capable or should be capable of being repeated. […] The classical scientific method relies on the control of the experimental environment and it relies on the control of key variables. This is very

> difficult to achieve in design research […] Thus when undertaking design research it is not possible to replicate the classical approach and new approaches are required.

These are difficulties to overcome and possibilities to explore, but what about the objection above about other architectural 'experiments' that claim they constitute actual experiments? There is a difference between an experimental work of architecture (an 'experiment' in the sense that it investigates a new design procedure) and a work of architecture *as an experiment* that doubles up as an 'architectural science experiment,' an actual experiment in the scientific sense). AAA holds that constructing an assemblage to be studied is an actual experiment if, and only if, the experiment can *fail*. This may sound obvious to seasoned scientists, used to recording their results in order that colleagues may build upon them, whether the experiment 'succeeds' or 'fails' (strictly speaking, a scientific experiment of course never fails, as it simply documents the outcome of a process, as opposed to aiming for a particular result). But it is counterintuitive for instance to many architects, used to 'conduct experiments' (test design procedures) that invariably produce successful outcomes, whether in architecture school (where 'failed' experiments tend to result in weak grades) or in commercial practice (where 'failed' experiments tend to result in disgruntled clients).

However, the AAA methodology seems to open a window of possibility when it comes to allowing for 'failed' experiments in architecture. The approach science uses to gain knowledge – based on making observations, formulating laws and theories, and testing theories or hypotheses by experimentation – can be extended to AAA architecture. When the experimental environment (the 'test rig' that Culley mentions) is the computer, and the control of key variables is the very act that produces the architectural proposals through experimentation, and when that controlling mechanism is based on a hypothesis drawn from background contextual investigations and modelling, and when all experiments are recorded and by the nature of the experimental set-up capable of being repeated, then it appears we have a system that ticks all the boxes for being able to replicate the essence of the scientific method as part of an architectural design method. And the sheer number of generated design iterations, together with the possibility to automatically record outcomes for each assemblage, makes design research at the big data level a possibility.

This insight has far-reaching consequences. It provides the AAA architect with the means to potentially carry out experimental work in each and every new project. In Woods (2010), the late American architect Lebbeus Woods noted that the 'task of the experimental architect is to take us to places and spaces we haven't been before'. If we take this statement at face value, it seems to imply that the experimental architecture traces a centrifugal trajectory whereas the scientific experiment aligns with centripetal forces: the former seeks to explore exotic virgin grounds, the latter to dissect the everyday world around us. A brief outline of the history of experimentation in architecture can be found in Brayer (2008).

In order to use a design methodology to produce actual scientific knowledge, we need protocols for conducting 'architectural science experiments' that produce a better balance between the centrifugal forces of experimental architecture and the centripetal forces of the scientific method. This thesis will suggest such a protocol, parametric epistemic things, introduced in the next chapter to follow.

EPISTEMOLOGY

6. EPISTEMOLOGY

Why do architects and engineers need an epistemology? Because such a philosophical examination of knowledge (predominantly its nature, methods, validity, and scope) promotes an active critical attitude that orients architectural thought, and because it is foundational to determining a proper method to evaluate the results of our efforts. The following is an attempt at constructing a AAA epistemology. It is not an accumulation of epistemic evidence. It will be taken for granted that overwhelming evidence exists to suggest that certain phenomena – knowledge, assemblages, capacities, potentials, constraints, and so on – are *real,* but no account will be given of *how* those arguments are constructed. An architectural epistemology needn't be bound by positivistic fact finding, but could rather ground a process of inquiry that opens up 'new lines of thought' with respect to different conditions and procedures; however, as Christenson (2009) points out, the tools we use to gain knowledge about something have an impact on what knowledge can be gained: 'study media are not neutral epistemological frameworks: researchers' choice of study media limits the kinds of questions they can ask of architecture'.

Hold that thought for a moment and let us ponder a question. The question is this: how do you figure out which people on Earth is the most ancient? If the year is 600 BC and you happen to be the Ancient Egyptian pharaoh Psamtik I, you open your scientific toolbox and pick up the instructions for the infamous 'forbidden experiment'. The reference manual tells you to give two newborn babies to a shepherd, with the instructions that no one be allowed to speak with them. Instead, the shepherd should feed and care for the children while listening intently (for years) to determine what their first spoken words are. The hypothesis, as Shattuck (1994) explains, is that those words will be uttered in the root language of all people, and that by way of deduction you will be able to tell which people has lived on Earth the longest. According to a rather unverified account by Herodotus (431 B.C.E.), one of the children eventually cried 'βεκός' (bekós), the Phrygian word for 'bread'. End experiment.

Scientific procedures carried out to support, refute, or validate hypotheses always rely on repeatable operations and logical analyses of their results (though they do not always rely on giving away babies to shepherds). As Griffith & Brosing (2009) attest, the *experiment* is an empirical procedure, an integral part of the scientific method that arbitrates competing models or hypotheses while allowing researchers to test existing theories or new hypotheses in order to support or disprove them. In AAA parlance, the experiment is an exploration of a an assemblage, component, or process within the variable confines of a set of parametric constraints. In the simplest sense, experimentation equals controlled exploration: the act of getting lost within a confined area. This is what AAAs 'intentionally' do. Their very nature is exploratory, and they document each exploration by producing a kind of map. At a level of tautological risk, AAAs are thus epistemologically morphogenetic.

As Delanda (1999) suggests, we may carry out a familiar thermodynamic experiment by creating a container separated into two compartments, filling one compartment with cold air and the other with hot air, thereby creating a system that embodies a difference in *intensity* (temperature). If we then manipulate the parameter that controls the opening of a small hole in the dividing wall between the compartments,

> the intensity difference causes the onset of a spontaneous flow of air from one side to the other. It is in this sense that intensity differences are morphogenetic, giving rise to the phenomena of experience, even if in this case the phenomenon that emerges is too simple. The main idea, however, is much more general: many phenomena, in geology, meteorology, biology and even economics and sociology, emerge spontaneously from the interplay of intensity differences. Indeed, one can build an entire theory of the genesis of form (of geological, biological or cultural forms) on the basis of processes of becoming driven by intensity differences. Unlike essentialism, where matter is viewed as an inert receptacle for forms that come from the outside (transcendental essences), here matter is seen as possessing its own immanent, intensive resources for the generation of form from within.

That matter has an immanent capacity to generate form is an important insight. However, 19th-century thermodynamics couldn't provide the foundation that DeLanda's philosophical progenitor Gilles Deleuze needed for a philosophy of form, since the entire discipline was focused to the point of obsession on final equilibrium forms. As DeLanda explains, this was

> at the expense of the difference-driven morphogenetic process which gives rise to those forms. In other words, intensive differences are subordinated to the extensive structures (structures extended in space-time) they give rise to. But as Deleuze argues, most of the important philosophical insights can only be grasped during the process of morphogenesis, that is, before the final form is actualized, before the difference disappears.

The implication to AAA seems clear: the final building gets in the way of what we might learn from the process of designing it. In the AAA process, however, morphogenesis produces not only form, but also information about that form: its properties and potentials. AAAs thus maintain their 'internal differences,' the output values that resulted from the creation of a form through the changing of input values. This 'unhiding' of intensive qualities from extensive results is key to unlocking the epistemic potential of AAAs. It is only in the interval between changing an input (creating a difference) and recording an output (when the difference disappears) that knowledge can be created. AAA epistemology takes place predominantly through morphogenesis.

Deleuze himself linked the shortcoming of classical thermodynamics (its persistent preference for the extensive over the intensive, its insistence on cancelling out difference to concentrate on the equilibrium) to a detrimental *epistemological* position:

> In truth, our epistemological tendency to be suspicious of the notion of intensive quantity would prove nothing were it not linked to this other tendency on the part of differences of intensity to cancel themselves out in qualified extended systems. Intensity is suspect only because it seems to rush headlong into suicide.

Before we move on, an important linguistic distinction needs to be made between two different meanings of the term epistemology, which was succinctly summed up by Rheinberger (2007):

> My use of the term epistemology requires a brief explanation. I do not use it as a synonym for a theory of knowledge (Erkenntnis) that inquires into what it is that makes knowledge (Wissen) scientific, as was characteristic of the classical tradition, especially in English-speaking countries. Rather, the concept is used here, following the French practice, for reflecting on the historical conditions under which, and the means with which, things are made into objects of knowledge. It focuses thus on the process of generating scientific knowledge and the ways in which it is initiated and maintained.

Our AAA epistemology adopts this latter usage. We are not aiming to construct an entire theory of knowledge in the classical sense, but to develop an architectural epistemology applicable to the domain under investigation – and to pragmatically extend this epistemology to a method for acquiring different kinds of design-driven knowledge. What we are interested in is how the AAA design process can be experimentally used to generate scientific knowledge and impart important philosophical insights 'before the difference disappears'.

The rest of this chapter discusses variety and constraint, brings up aspects of AAA's epistemic potential, introduces the concept of parametric epistemic things (PET), and suggests ways in which they can be used to allow for future automated AAA experimentation.

6.1 Variety and constraint

Deleuze condescendingly refers to the essentialist model of morphogenesis as the 'hylomorphic schema'. This of course refers to Hylomorphism, the central doctrine of Aristotle's theory of nature, which conceives being as a compound of matter and form, or, rather, maintains that matter is an inert material that exists for the sake of receiving form. This view has important teleological implications to which we shall return in the chapter on axiology, but for now let us just point out that the idea of matter as somehow waiting to have a form imposed on it from the outside is entirely incompatible with the spontaneously emerging self-organisation of forms that Deleuze (and following him DeLanda) promote.

If we appear to linger with notions of form when we should be discussing knowledge, it is because as architecture is ultimately concerned with the production of form (or space), so AAA epistemology is by definition an epistemology of the creation of material forms. Our intent, to echo the Rheinberger quote above, is to investigate the conditions under which (and the means through which) anticipatory adaptive assemblages can be made into objects of knowledge, and how this knowledge-generating process can be initiated and maintained.

To achieve this, we need to consider how the AAA itself is initiated and maintained so as to better understand where in that process knowledge can be created and extracted. As we have seen in previous sections, these assemblages are designs controlled by what mathematician and systems analyst Horst Rittel – who in Rittel & Webber (1973) famously designated design problems as 'wicked problems,' contrasted with the 'tame problems' of science – called 'the generation of variety, and the reduction of variety' (Protzen & Harris 2010). Fischer & Richards (2017) link this idea to cybernetician Ross Ashby's work on variety (summed up as the 'relation between two sets [that] occurs when the variety that exists under one condition is less than the variety that exists under another,' see Ashby (1956)), and then connects it to the definition in von Bertalanffy (1968) of a system as a set of 'elements standing in interrelation,' stating that some thinkers

> differentiate von Bertalanffy's definition by recognizing the existence of systems in contexts or environments, and the interaction of systems with their environments via inputs and outputs that cross a given system's boundaries. Further differentiations ascribe more characteristics to systems, i.e., goal-oriented systems and self-perpetuating systems. Weinberg [2001] introduces a subjective, observer-dependent aspect by defining system as '[a] way of looking at the world,' and Rittel [1992] states that a system 'reflects someone's understanding of something'.

This reference appears to introduce a conflict to our argument. We wish to state precisely that AAA is a way of looking at the world, that anticipatory adaptive assemblages 'reflect someone's understanding of something' but not at the cost of making the assemblage observer dependent. Brün (2004) seems to be patently wrong when he asserts that a system

> is not something that exists objectively in space or time or anywhere. A system is the result of a look at a collection of stipulated elements. Stipulated in that I say which elements I will look at.

The famed composer and pioneer of electronic and computer music may of course look at any elements he like, but that does not mean that a system (such as a work of architecture, say, or a shepherd, or the Phrygian language) ceases to exist when he turns his gaze away, or that it did not exist until he willed it into existence. The fact that we can *choose* to view a collection of heterogenous components (an assemblage) as being part of several different systems (assemblages) – Fischer & Richards (2017) mention the system of a child who without the care and feeding of her mother wouldn't survive and through this dependency becomes part of another system that includes the mother; Bateson (1972) similarly mentions the integrated 'tree-eyes-brain-muscles-axe-stroke-tree' feedback system composed of a lumberjack felling a tree with an axe – does not mean that these assemblages do not exist until we decide that we will designate them as assemblages. It means that *finding* them, we can recognise them as being assemblages (that may or may not be of the knowledge-generating kind).

Bateson's point, if we allow ourselves to extrapolate it for our purposes and reposition it within the context of AAA theory, is that an assemblage within which a biological event is determined usually does not have the same boundaries as the assemblage of the individual organism 'carrying out' the event. This comes as no surprise, as we have already seen that architectural assemblages are always composed of heterogenous components, assemblages within assemblages.

However, such a nesting of assemblages also carries a temporal implication: the lumberjack, having felled the tree and put away his axe, is arguably no longer actively a part of the assemblage he initiated (though he remains a *virtual* part of future *potential similar* assemblages if other trees need to be felled). Likewise, an AD (assemblage) may for instance initiate and maintain a AAA (thus forming an integrated assemblage with it), but can at a later stage conceivably opt to withdraw from the role of actively controlling it to instead analysing its effect, thus shifting roles between designer and analyst of the designed assemblage's behaviour. (All of these acts – initiation, maintenance, control, analysis – could also in principle be automated.)

The statement that AAAs 'reflect someone's understanding of something' begs the question: whose understanding, and of what? To answer these questions, we need to probe deeper into the idea of variety and the reduction – or constraint – of variety. To Rittel (1992), constraints define and delimit parts of the design space that are excluded from further consideration, pointing towards what Heylighen (1995) defines as 'a system as a constraint on variety'. It is important to remember that we can constrain the variety of each assemblage at any scale: assemblage A can be constrained, and/or assemblage B, and/or the combined assemblage AB.

6.2 Aspects of epistemic potential

Five aspects of AAAs make them particularly well suited for epistemic exploitation: 1) their exploratory (and thereby inherently experimental) nature, 2) their explicit use of well-defined constraints, 3) their anticipatory capacity, 4) their uncritical acceptance of problem statements, and 5) the fact that they can maintain their internal differences and keep them from cancelling themselves so that intensive processes are not hidden underneath extensive results. Let us review these aspects one by one in further detail to better understand the limitations and potentials of this AAA epistemology, before moving on to turn this understanding into a practical method for turning AAAs into Rheinberger's 'objects of knowledge'.

1) The first of these aspects is arguably the most important to the present argument, and as such will be examined in particular detail. As we have seen, AAAs explore demarcated design spaces in pursuit of solutions to geometrically driven multi-objective optimisation challenges. The basic unit and epistemic currency of AAAs is exploration. Exploring is what AAAs are about, just as exploring a demarcated space of inquiry is what experimentation is about. In any design endeavour, but in particular for an AD using AAAs, every new design process doubles up as an experiment, an exploratory inquiry with the capacity to yield objects of knowledge.

Ammon (2017) argues vehemently *against* this position, claiming that designing 'should not be regarded as a kind of experimenting' but as 'an independent epistemic praxis'. This is in stark contrast to Schön (1983), a book that Ammon agrees 'revolves around the core thesis that designing – as "reflection-in-action" – relies on experimenting'. This idea, writes Ammon, offers 'a powerful and alluring fall-back position,' for

> if it can be successfully shown that methods used to design something are used equally for the purpose of experimenting, then this would bestow upon the domain of design the status of a scientific endeavour; it would prove that designing is a research activity much like those found in the natural sciences. More than this, though, this methodological claim entails an even more important epistemological one. If designing turns out to be a powerful research activity, then it must also be a

> means of knowledge acquisition and, hence, a domain of genuine knowledge as opposed to mere applied knowledge.

Ammon argues that this is wrong because ‘to highlight parallels between designing and experimenting is to obscure the genuine epistemic practices and strategies of knowledge acquisition involved in processes of designing’. Ammon’s well-argued point is that the routine use of scientific methods employed to dismiss as inferior activities with other characteristics and approaches threatens the independent epistemic praxis of design. (In other words: designers produce knowledge of a different kind than the knowledge produced by scientists.) Following the definition in Hatfield (1998) of experiments as ‘procedures for attaining scientific knowledge,’ Ammon produces a narrow notion of experiment as a method elaborated within science, the introduction of which has the effect that ‘scientific effort is no longer confined to pure descriptions of nature but rather opens up to the discovery of general laws that describe the structure of conditions and allow prediction and manipulation’.

Ammon then points to the three kinds of experiment that Schön claims can be found in *both* design and science: *exploratory* experiments (‘actions performed in order to see what happens, without being embedded in predictions or expectations’), *move-testing* experiments (‘actions performed in order to achieve an intended change’), and *hypothesis-testing* experiments (‘actions aimed at discriminating among competing hypotheses found implicitly in the pattern of the moves’). Apparently resigning this line of inquiry (‘Schön’s study provides strong arguments for defending the thesis that designing is indeed an epistemic praxis (enabling) genuine knowledge to be generated. What is not yet demonstrated, though, is that the two epistemic praxes of designing and experimenting belong to the same category’), she moves on to consider three of the seven aspects that Gonzalez (2007) uses to define the practice of experimentation.

Ammon’s first objection is that in a design context, science’s demand for repeatability would immediately be classified as plagiarism; that ‘the characteristic lack of repeatability in design, which constitutes a methodological virtue […] must not be confused with the lack of repeatability in science, which is reported as methodological failure’. Against this can be argued that while the random (mutation) element of evolutionary computation makes exact repeatability of individual AAAs a difficult prospect, this does still not void the potential of conducting comparative studies of phenotypes at the level of a species, or of studying aspects (such as energy performance relative to form seed) that are not synonymous with the exact replication of a metric or effect. If this were the case, it would for example be impossible for biology to be classified as a science, as not every child or shepherd has the same weight.

Ammon’s second objection is that contrasted to the narrow sense of experimentation used in the natural sciences, which is ‘geared towards real-world phenomena,’ designing ‘is projective’ and ‘seeks to make manifest something which is non-existent and which might never exist,’ which supposedly ontologically leads to the conclusion that ‘designing explores the non-existent (or not yet existing) world whereas experimenting explores the existing world’. But this argument seems to fall into the ontological trap of mistaking that which ‘exists’ (is actualised) with that which is real. There is nothing to say that the millions upon millions of virtual and never-to-be-actualised phenotypes typically generated by AAAs are anything but real. They have the capacity to become objects of knowledge and can certainly be scientifically studied, just as the study of, say, complex adaptive systems, or cellular automata, is a scientific endeavour. But don’t just take this author's word for it – in Feferman et al. (1986), legendary mathematician Kurt Gödel’s view is summed up thus: ‘mathematical objects have an independent existence and reality analogous to that of physical objects’.

Ammon’s third objection is to do with the purported epistemological difference between designing and experimenting. ‘Due to the ontological situation and the projective nature of design, only the notational exploratory setup is able to provide answers; there is no outside authority that might serve as a neutral judge,’ however there are techniques and methods that ‘make it possible to continually check the evolving design. Used in combination with particular tools and design artefacts, these practices help designers to implement epistemic strategies, that is, endeavours that actively pursue epistemic objectives and are an integral part of epistemic praxes in general’. Ammon appears to cancel this objection

> in order to transfer insights deriving from a design process into a systematized explicit body of knowledge, a reflexive moment must come into play, a moment that methodically checks, evaluates and organizes underlying processes. This kind of design research already differs from the original activity of designing in its critical distancing, systematization and generalization as well as in its practices of transmission and dissemination of results, all of which are embedded in scientific work. As soon as these aspects come into play, then the praxis in question is no longer the epistemic praxis of designing but is part of a comprehensive science of design.

While designing can certainly be viewed as an important independent and effective epistemic praxis, the lingering question is this: why do we need to choose between the praxis of design and the praxis of experimentation? The AAA methodology provides a framework that turns this either/or situation into a both/and counterpart, effectively infusing science with architecture and architecture with science. The ‘reflecive moment’ is automated, built into the computational process of AAA morphogenesis. There is literally no difference between this (design) research and the ‘activity’ of designing – they are coexisting, mutual, inhabiting the same space. Following Maher (2000) and Dorst & Cross (2001), we may define the AAA design process as co-evolution of problem and solution space.

Having confronted the objections of Ammon at some length to defend the notion that the exploratory nature of AAAs inherently makes them valid candidates for scientific experimentation, let us move on to the four other aspects in our list of primary epistemic potentials.

2) The explicit use of well-defined constraints, obviously crucial to the development of AAAs, turn them into objects of knowledge simply by virtue of having a defined design space. (Already from this humble beginning a plethora of studies could be made, to answer questions such as: Which genetic algorithm is most efficient in solving this particular optimisation problem? What is the correlation between the design of the constraints and the

topography of the fitness landscape? What is the correlation between phenotypic quality and increased or decreased levels of constraints?).

The use of constraints could be presumed to make AAAs less teleological (goal oriented). But as Fischer & Richards (2017) point out – perhaps surprisingly since goal-oriented approaches are conventionally described as procedures in which goals give direction while constraints limit freedom, and contrasted with constraint-oriented approaches in which constraints give direction while goals limit freedom – it is quite possible to 'engage in goal-oriented and constraint-oriented processes simultaneously'. These opposing approaches can be merged into a dialectical process, in which goals are primarily concerned with what one specifically wants, and constraints with what one does not want. 'However,' continue Fischer and Richards,

> any goal can be turned into a constraint, and any constraint into a goal [...] there is a fundamental difference in thinking between the two approaches, with a goal-oriented approach representing a point (or vector) way of thinking in which future achievement is the driving force and a constraint-oriented approach representing a spatial (or even topological) way of thinking in which avoidance in the here and now is the driving force.

The former narrows probable outcomes, while the latter expands possible outcomes. This dynamic process not only supports creative design applications, but encourages epistemic explorations: we might, for instance, exploit the nature of the two methods to investigate the relative strengths of vector-based vs topological approaches in the light of different challenges, knowledge that can be used in the design of future AAAs.

3) The epistemic mechanisms of the anticipatory capacity of AAAs are primarily related to various kinds of simulations. As Zamenopoulos & Alexiou (2007) note, anticipation indicates the capacity to act in preparation for a certain effect or future state of the world. This idea is arguably foundational to most architectural endeavours (buildings typically feature a roof because their owners do not wish to get wet) as well as to most epistemological undertakings (pharaos who give babies to shepherds typically hope to learn something from the process). In the field of design research, it has been part of the literature at least since Fuller (1963). Ever since Rosen (1985) introduced anticipation as a biological concept in relation to the study, modelling, and control of complex systems, it has been part of the avant-garde architectural discourse. Notable examples of later scientific treatments include Dubois (1998, 2000), who suggests anticipation is fundamentally present not just in biological but in all physical systems; Nadin (2003), who focuses on the challenge to the ruling cause-and-effect paradigm in the physical sciences; and the teleodynamics concept developed by Deacon (2012).

Since anticipation is as an important aspect for understanding, modelling, and even constructing reality, and since it is also strongly related to scientific investigation, the anticipatory capacity of AAAs has great epistemological potential. The notion *a phenotype within* the assemblage 'running ahead in time' to carry out a simulation, the results of which are then fed back to influence the evolution of *the entire assemblage* points to a dual epistemic function: knowledge is being accumulated internal to and informing the AAA itself, while the *accumulated effects* of this knowledge is then being communicated as external data.

There are also compelling economic, environmental, and social reasons to use anticipation in design. As Aksamija (2016) explains:

> today, designers and their patrons are increasingly seeking proof that design will live up to expectations in the future. This yearning for predictability is pushing designers to balance their humanistic focus on what has been and what is, with a scientific rigour that attempts to establish what will be. This accelerating move towards fact-based predictive design thinking is revolutionising our creative process far beyond the limited aim of reducing risk, towards a new form of design practice that bristles with empirical discipline in balance with imagination.

Mechanisms of anticipation and simulation require that we do not equate knowledge with absolute truth. In Dretske (2008), the author proposes (between the lines) that the possibility of knowledge hinges on the communication of information. Information, for Dretske, 'must be true' (as opposed to meaning, which may not be true), and 'knowledge is knowledge of the truth'. This, however, seems overly strict: isn't indicative information – 'the sky is beginning to bruise' – also a type of knowledge, information that we can use for instance when considering whether to pack an umbrella? Similarly: does it not seem prudent to allow projective and indicative simulations-based data to guide the digital morphogenesis of a AAA geometry?

Whether or not simulation in engineering science is a kind of experimentation is the subject of an ongoing debate – see for instance Winsberg (2015) and Schiaffonati (2016). Be that as it may, and again suspending the disbelief introduced by Dretske above, the simulations driving the anticipation mechanisms within AAAs represent what Campbell (1974) and Schmidt Galaaen (2006) might recognise as a kind of downward causation-induced exploration that generates knowledge about potential future states, an *epistemology of the probable.* This knowledge in fact directly controls the system, as it simulates effects of the choices made, feeds back the information to the assemblage, and allows it to attempt to modulate its settings in pursuit of better solutions, given the predefined targets. According to Alexander (1964), 'scientists try to identify the components of existing structures, (while) designers try to shape the components of new structures'. But the epistemic mechanisms at work within AAAs make the assemblage do both at the same time: shaping phenotypes *while* identifying their properties and potentials.

4) The uncritical acceptance of problem statements of AAAs are next on our list. Let us begin with the latter: in the introduction, we already touched upon this uncritical acceptance offered by AAAs in our tongue-in-cheek admission that the underlying technology itself could be misused by a sinister architect wishing to increase a building's level of fascist-ness. The epistemological implication is that the assemblages can be designed to begin to investigate almost any conceivable area of inquiry. Interested in exploring differences in material weathering effects, circulatory efficiency, generative space syntax, or high-performing façades? AAA has got you covered.

5) Finally, as with the far-from-equilibrium thermodynamics that superseded its 19th-century counterpart, if continuously traversed by a flow of resources – typically time, money, and computing power – AAAs can maintain their internal differences, keeping them from cancelling themselves. This way, intensive processes are not hidden underneath extensive results, but are allowed to remain intensities, and the optimisation process can in principle keep going forever (in practice until the resources run out). We shall return to this theme at the end of the chapter, as we discuss automated experimentation.

6.3 Parametric epistemic things (PET)

DeLanda (2015) is an intellectual cartography of the processes of variation and differentiation that gradually and over time shaped the history of the field of chemistry, an ingenious attempt

> at creating a model of a scientific field capable of accommodating the variation and differentiation evident in the history of scientific practice. […] The model is made of three components: a *domain of phenomena,* a *community of practitioners,* and a set of *instruments and techniques* connecting the community to the domain. The domain of a scientific field consists of a set of objective phenomena. The term 'objective phenomenon' refers to an effect that can emerge spontaneously or that, on the contrary, might require active interventions by an experimenter to refine it and stabilize it. The former case is illustrated by the celestial phenomena studied by astronomers, while the latter is exemplified by laboratory phenomena.

Where does this leave the field of AAA? Cross (2006) distinguishes between *scientific design* that refers to 'modern, industrialized design based on scientific knowledge,' *design science* that refers to 'an explicitly organized, rational and wholly systematic approach to design' and *science of design* that refers to 'that body of work which attempts to improve our understanding of design through "scientific" (i.e. systematic, reliable) methods of investigation'. The epistemic status of AAAs as 'objects of knowledge' arguably allow all three of these design methods to be employed, but the position of the latter – science of design – may allow us to use DeLanda's instruments and techniques that connect a domain of phenomena to a community of practitioners to try and gain a better understanding of how the AAA method and theory may be extended to produce epistemically systematic and reliable investigations.

In Rheinberger (1997), an epistemological treatise on 'the iterative enforcement of a local research system and its subsequent dissemination,' historian of science Hans-Jörg Rheinberger introduces his notion of 'epistemic things,' the 'significant units' or 'objects of research' that experimental scientists deal with in their daily bench work. Rheinberger holds the sciences to be a 'permanent process of reorientation and reshuffling of the boundaries of what is thought to be known and what is beyond imagination'. His epistemic things are what scientists configure and reconfigure during that process, only to be met 'with resistance, resilience, recalcitrance'. Epistemic things are in fact unexpected phenomena emerging from 'technical objects' (the actual object of investigation during the research process) subjected to specific forces or brought into particular constellations within an 'experimental system'. (It should be noted, however, that Rheinberger's epistemic things can be transformed into technical objects and vice versa – epistemic things turned into technical objects can be used to research other epistemic things.)

According to Borgdorff (2012), experimental systems ('a basic unit of experimental activity combining local, technical, instrumental, institutional, social, and epistemic aspects') are in turn 'characterised by the interplay and entwinement of "technical objects" and "epistemic things" – the technical conditions under which an experiment takes place and the objects of knowledge whose emergence they enable'. Such systems function as 'generators of surprises,' and through 'conjectures and bifurcations' (the result of 'unprecedented and unanticipated events'), particular experimental systems grow into research agendas as they 'get linked into experimental ensembles, or experimental cultures'.

The experimental system, writes Rheinberger,

> can readily be compared to a labyrinth, whose walls, in the course of being erected, in one and the same movement, blind and guide the experimenter. In the step-by-step construction of a labyrinth, the existing walls limit and orient the direction of the walls to be added. A labyrinth that deserves the name is not planned and thus cannot be conquered by following a plan.

Within the present 'labyrinthine' context of evolutionary architectural design (the chosen domain, or experimental system), the AAA design definition of an assemblage produced and presented as (for instance) a Grasshopper user object can be viewed as a digital vehicle capable of producing the unexpected phenomena that characterise Rheinberger's epistemic things. Following the discussion above on DeLanda's parametrisation of assemblages, we propose to call such digital developments of Rheinberger's original concept 'parametric epistemic things' (PET). The parametric and anticipatory nature of a AAA seems to make the connection between the original physical epistemic thing and its digital counterpart a particularly strong one: according to Rheinberger, epistemic things 'emerge from the deposit of the technical and its potential for tinkering' and 'are recursively constituted and thus intrinsically historical things. They derive their significance from their future, which is unpredictable at the real time of their emergence'. They are, then, a sort of anticipatory system, virtual until actualised.

Newman & Tarasiewicz (2013) point out, in relation to Rheinberger's initial concept, that the ideas 'that "artists create things" and "scientists discover things" are not mutually exclusive; scientists must also create to discover'. Arguably, the evolution of a PET framework for the architecture and engineering disciplines, based on the method of creating parametric epistemic things and allowing others to use them to create and investigate their own unexpected phenomena, could be a fertile way forward for the design and methodology of AAA (and by extension building science) experiments.

Extrapolating from Rheinberger, such a AAA-based PET framework might be constructed using the following initial protocol: a design challenge is confronted by the construction of a parametric assemblage with variable inputs. These may be very simple – values for changing the dimensions of a box-like geometry, say – or they may be quite complex, as would be the case if they are, say, values associated with simulated projections of future climate scenarios.

This parametric assemblage (DeLanda) ‘becomes’ a parametric epistemic thing (Rheinberger) by virtue of being set up like a laboratory experiment. Instead of a traditional work bench, an algorithmic programming environment is used (in our case Grasshopper), but other than that, the procedure is much the same as in the physical lab, and essentially follows the structure of a typical lab report (which generally aims to document one’s findings and communicate their significance).

The PET could conceivably be optimised even further by becoming part of other assemblages that allow it to be automated and to generate (and interact with flows of) big data. We will conclude this chapter by considering in further detail such extensions of the PET idea.

6.4 Automated experimentation

Automating the PET experiments is a potentially interesting way of leveraging the concept of parametric epistemic things. Radder (2009) identifies the role of automation processes in experimental research, pointing out that in order to perform experiments,

> whether they are large-scale or small-scale, experimenters have to intervene actively in the material world; moreover, in doing so they produce all kinds of new objects, substances, phenomena and processes. […] a central issue for a philosophy of experiment is the question of the nature of experimental intervention and production, and their philosophical implications.

If PETs are used, maybe the AD experimenters need only to intervene once, when setting up the experiment? Researchers typically want their experiments to be stable and reproducible, which requires solid knowledge and meticulous control of the interactions between a system and its environment. This is indubitably the case with the kind of digital and mathematical experiments we are discussing here, which test one or several AAAs by treating them as PETs. Morgan (2003) pits experimental demonstration against mathematical demonstration:

> In laboratory experiments we intervene in the material system to produce material results for the particular situation found in the experimental setup. In the mathematical model experiments […] the ‘intervention’ into the model begins with a question that prompts the deductive or logical reasoning power of mathematics to derive the results. This difference between producing or deriving results is the contrast between experimental demonstration and mathematical demonstration.

Morgan goes on to suggest that some experiments could be treated as hybrids between such experimental and mathematical demonstrations, and proposes a taxonomy of

> hybrid things ‘in between’ that include virtual experiments (entirely nonmaterial in object of study and in intervention but which may involve the mimicking of observations) and virtually experiments (almost a material experiment by virtue of the virtually material object of input).

This has a familiar ring to it. Aren’t the phenotypes produced by the form seeds in AAAs precisely the hybrid outcome of such experimentation, models (actual digital 3D models that if need be can be made physical through various prototyping or fabrication strategies) that are also experiments, mathematical representations that are also able to demonstrate different responses to experimental questions ('which combination of in-data parameter settings produces the desired out-data properties?'), a range of simplifying assumptions that yield the possibility of applying experimental constraints. Isn't such a method a firm refusal to separate theory from experiment from evidence? Radder (2009) notes that

> recent scientific practice shows an ever-increasing use of 'computer experiments'. These involve various sorts of hybrids of material intervention, computer simulation, and theoretical and mathematical modelling techniques. […] Automated experimentation constitutes a significant part of these developments.

To find plausible and innovative ways to carry out automated experimentation, Sparkes et al. (2010) describe a 'robot scientist,' a system that 'uses techniques from artificial intelligence to automate all aspects of the scientific discovery process: it generates hypotheses from a computer model of the domain, designs experiments to test these hypotheses, runs the physical experiments using robotic systems, analyses and interprets the resulting data, and repeats the cycle'.

To accomplish a *full automation* of a PET-based AAA discovery process, the assemblage needs to 1) create the initial hypotheses that define the reasons for carrying out the experiments, and 2) be capable of learning from the results. That is, it needs to be endowed with three types of logical reasoning used in scientific discovery: deduction, induction, and abduction. Deduction enables the inference of valid facts from existing known facts and rules, induction enables the inference of hypothesised rules from known facts, and abduction enables the inference of hypothesised facts from known facts.

Furthermore, the full automation of the epistemic aspects of AAA requires 'closed-loop learning,' where the assemblage not only analyses the results, but learns from them and feeds the resulting knowledge back into the next cycle of the process. Computational closed-loop learning systems have certain advantages over human scientists: their biases are explicit; they can produce full records of their reasoning processes, which makes the investigations more reproducible and reusable; they can incorporate large volumes of explicit background knowledge as well as highly complex models; they can analyse data much faster; and they never need the bathroom.

The particular kind of assemblages comprised by PETs carry an obvious future potential. They can be used to provide scientific rigour to the domain of architecture and engineering, which often focuses on pragmatic issues to the detriment of academic research. Furthermore, any prosperous components of our methodology – form seeds, objective functions, constraining components, analytic tools, simulation set-ups, evolutionary solver settings, and so on – can be distributed with the PET and shared between researchers. This is similar to how Nelson & Winter (1982) observed that in economic evolution, as contrasted with biological evolution, successful algorithms may be borrowed by one firm from another:

> any new idea can be incorporated in operating procedures as soon as its success is observed, and hence successful mutations can be transferred between firms. Transfer is of course not costless, but involves learning costs for the adopting firm.

At this early stage, the development of the PET framework primarily needs to investigate how different protocols that ensure reproducibility and falsifiability could be introduced, and what their relative merits are. It seems clear that at least parts of the research process could be automated, as evolutionary 'runs' can be set up to work on experiments in architecture science and building science 'in the background,' reporting back interesting results as and when they arise. However, in any design-led research environment, the full process will never be automated. As noted in Plowright (2014), the AAA architect will not be replaced by a robot anytime soon:

> Philosophical approach, starting bias, and selection of elements in the design are the role of the designer, not of the method. None of these aspects can be automated as they are non-linear and complex. None of them can be reduced to discrete, isolated problems.

These aspects, then, will be the primary considerations of the AAA architect when doubling up as epistemological experimenter, who in her or his development of discrete AAAs will simultaneously continue the development, or evolution, of not just a novel research method but a new kind of materialism in architecture and engineering – one that from an uncompromisingly realist position infuses theories of architectural materiality with notions of anticipation, adaptation, and assemblage thinking. Let us now turn to a discussion of how this evolutionary materialism might be shaped by the hidden control mechanism of AAA: its generative value system.

AXIOLOGY

7. AXIOLOGY

Why do architects and engineers need an axiology? Because such a philosophical examination of *value* (which among other things provides the foundation for fields such as ethics and aesthetics) provides us with the means to tell whether our work is 'right' and 'good' and 'beautiful' and 'beneficial,' while framing our endeavours in terms of their human, social, economic, and environmental progress and sustainability.

While ontologies are primarily concerned with questions of *what* exists, *why* anything comes into being, and *how* change happens, architecture is fundamentally the art and science of what *could* exist, or, in an even more axiological approach, what *should be made* to exist – in terms of buildings and cities and other structures, but also implicitly and/or ultimately with regards to aspects related to the social sciences, such as the human behaviour, psychological welfare, social organisation, demographic development, economic attitudes, scientific positions, technological progress, and political theories that those buildings and cities and structures support.

An axiology of architecture and engineering is thus a study of the various roles of value in the built environment. The term was first used by Lapie (1902), followed by von Hartmann (1908). Hartman (1967) formalised the field into a science of value. While ethics and aesthetics are the two principal domains associated with axiological studies, the present thesis holds that AAA – which uses numerical values to engender axiological (as well as, for instance, economic) values – might best be viewed as a theory capable of generating form through the interrogation of any combination of values, that is, through the very mechanism of valuation. Those mechanisms are the topic of this chapter, which introduces the axiological hypothesis, provides a catalogue of valuation operations, discusses immanent frames of possibility, ethics, and aesthetics.

7.1 Valuable architecture: The axiological hypothesis

To carry out a study of value, we must first understand the confines of the term itself. Value denotes both quantity and quality in many fields, the most important of which (to the current discussion) may be mathematics, physics, psychology, meteorology, economics, and ethics. Viewing value as a quantity, magnitude, or number, rather than as an axiological quality, we may for instance read a thermometer mounted outside our window and note a value of -6°C. This (mathematical) number can be viewed as a (physical) scalar quantity: a (meteorological) magnitude expressing outdoor temperature, which also (chemically) happens to be the freezing point of olive oil.

But this value could also be (psychologically) used as a stimulus ('I better put on a jacket when going out to check on those bottles of olive oil'), or as a value judgement – an injunction that implies an obligation to carry out some act, implicitly involving terms such as 'ought' or 'should' ('I shouldn't have left those bottles of olive oil outside'). If the thermometer value is associated with an economic enterprise (if, for instance, we are in the business of selling olive oil), then a financial value, a *potential* linked to price through the mechanism of exchange, might be directly affected by the circumstances causing the value recorded by the thermometer.

But value is also a term for the principles or standards of our behaviour and existence. To stick to the above example, the temperature reading might provoke an ethical discussion: 'If our olives were genetically modified, their oil could possibly be made to withstand lower temperatures, but genetically modified organisms raise concerns about allergies, cancer, and various environmental effects'. Such deliberations are positioned within a *value system*, a set of consistent values used for the purpose of ethical inquiry and ideological integrity.

The term 'value' is etymologically connected to the Latin word 'valere' which means to 'be worth'. A 'value' thus implies a worth, desirability, or utility of something. The act of attaching value to something – *valuating* – makes that value *instrumental*. As noted in Dewey (1916), to value means

> primarily to prize, to esteem; but secondarily it means to apprise, to estimate. It means, that is, the act of cherishing something, holding it dear, and also the act of passing judgment upon the nature and amount of its value as compared with something else. To value in the latter sense is to valuate or evaluate. The distinction coincides with that sometimes made between intrinsic and instrumental values. Intrinsic values are not objects of judgment, they cannot (as intrinsic) be compared, or regarded as greater and less, better or worse. They are invaluable; and if a thing is invaluable, it is neither more nor less so than any other invaluable. But occasions present themselves when it is necessary to choose, when we must let one thing go in order to take another. This establishes an order of preference, a greater and less, better and worse. Things judged or passed upon have to be estimated in relation to some third thing, some further end. With respect to that, they are means, or instrumental values.

Instrumental values can be used to generate architectural form. The axiological hypothesis of AAA is that architectural structures produced according to its methodology is founded in *valuation,* a wording appropriated from Neville (1981). This hypothesis suggests that the foundational structure of AAA is composed of (at least) six *operations of valuation:* 1) parametrisation, 2) quantification, 3) implementation of constraints, 4) application of objectives, 5) evolutionary evaluation, and 6) evaluative evolution. In various decisive and critical ways, these operations specify values that generate architectural form, thus turning AAA into an inherently axiological system capable of producing valuable (useful and important, but also, following Dewey above, *measurably* and *proportionally* useful and important) architecture.

At the basic mathematical level, these values (quantities) define the domains, ranges, variables, elements, and data sets that determine the virtual design space of the objective function that produces the assemblage. Combining different values typically yields different outcomes. As touched upon in section 2.4, it is important to note that AAA is agnostic with respect to *what* values are being used: the axiological frame needs to be constructed anew for each anticipatory adaptive assemblage. This process is linked to ethics and aesthetics, and furthermore links the (axiological) values of the mechanisms controlling the assemblage to the (mathematical) values that configure it, by way of *immanent frames of probability*. We shall return to this topic in section 7.2 below, but let us first briefly consider each of the six operations of valuation at the heart of AAA:

i) Parametrisation

The initial flurry of excitement over 'parametricism,' the reintroduction of the parametric paradigm in architecture carried out by architect Patrick Schumacher (2009), soon turned into a certain fatigue over its apparently ubiquitous seamless and sinuous geometries digitally rendered at short focal lengths, and with its associated high-minded rhetoric. (Interviewing the man behind the term in The Observer, architecture critic Rowan Moore (2016) noted with the driest of wits that Schumacher's attempt at explaining what he claims is a new 'style' of architecture featured an 'impressive but impenetrable string of polysyllables'.)

The history of the use of parameters in architecture is essentially as old as the discipline itself (see Davis (2013) and Assasi (2019) for historical accounts), since any dimension can be viewed as a parameter (if a wall is made longer or shorter by changing a line on a drawing, moving a point on a computer screen, or pacing out a certain number of feet in the sand, its length is being parametrically controlled). There is no such thing as nonparametric architecture. Parametricism used the idea of explicitly using parameters as a creative starting point for the generation of architectural form, and, as we have seen, Manuel DeLanda made a philosophical translation of the same idea by equipping Deleuzian assemblages with 'control knobs' for his assemblage theory. AAA shifts the focus by accepting this as the standard procedure of architectural production (changing parameters is essentially the job description for any designer, including architects and engineers) and emphasising instead the strategic calibration of the *mathematical domains* of those parameters.

A parameter's domain is the set of all possible input values that produce a valid output from a particular function, that is, the set of all values for which the function is mathematically defined. A valuation takes place whenever such a domain is defined: since many mathematical functions can accept any input, it is quite common for the domain to be the set of all real numbers (and for this variable to be denoted x), but the domain can also be more stringently circumscribed. In practical terms, this can be a way to mitigate the 'curse of dimensionality' – an expression coined in Bellman (1957) and discussed in Paper IV and Paper V – which can give rise to a number of issues when analysing data in high-dimensional spaces. The introduction of more parameters equals longer and more involved optimisation processes; cropping the domain is one way of alleviating this impact. (Allowing a building to rotate in increments of, say, 15° instead of 1° can significantly reduce computing times while perhaps still producing acceptable results.)

The important axiological consideration is that the adjustment of parametric domains is a value-driven procedure that carries obvious consequences for the resulting geometries. To continue the rotation example: given an assemblage based on a form seed that is composed of two boxes, the uppermost of which can be rotated 360° about its base plane centre point, we can choose two different step sizes: 1° or 15°. This of course produces two different domains, the first producing 360 possible configurations, the second 24 possible configurations. Some of the configurations produced by the longer domain are likely to yield a better outcome than the shorter domain, but at a higher computational cost. The study of such computational value decisions thus have a high ethical and aesthetic significance, as they directly impact the resulting geometries (aesthetics) as well as their associated performance metrics (ethics).

ii) Quantification

The parametrisation of the world necessary for architectural production in general and the production of AAAs in particular thus interconnects the two main axiological themes, ethics and aesthetics. Producing a different performance value – lowering the amount of embodied energy in the material composition of an assemblage, for instance – produces both a (primary) ethical and a (secondary) aesthetic effect. Note that in this specific example, the change may or may not be of a geometrical nature: if a new material is introduced that is compositionally different from but dimensionally identical with that which it replaces, no geometric change will of course take place.

This connection is made by way of quantities – features of the world that can be represented using a numerical scale, such as amounts of mass, wavelengths of light, and spatio-temporal distances. As Eddon (2013) shows, such families of quantities have two distinguishing characteristics: they can be ordered (10mm is *longer* than 5mm) and they are related by distance to one another (12mm is *closer* to 10mm than it is to 20mm). The ordering and closeness structure of quantities are symmetrically mirrored by the ordering and closeness structure of numbers, and so numbers can be used to transparently represent quantitative structures. In an interesting footnote, Eddon admits that

> we could use a numerical scale to represent other sorts of properties as well. But the results would be somewhat contrived. Consider the determinable being a shoe and its determinates: being a sneaker, being a dress shoe, being a sandal, etc. One might represent these properties using a numerical scale by, say, mapping being a sneaker to the number 1, being a dress shoe to the number 2, and so on. But in these cases the representation is clearly artificial, and does not capture anything interesting about the nature of the determinates.

So not everything can be quantified, at least not in any meaningful way. And many things are hard to quantify, as Koren (2018) decisively showed by launching an investigation into whether tennis balls are actually yellow or green. But in order to use something as a parameter it has to be valuated, and in order to valuate something it must be quantified, meaning it must be measured. Measurement is an integral part of modern science and engineering. And yet, as Tal (2020) notes, 'there is little consensus among philosophers as to how to define measurement, what sorts of things are measurable, or which conditions make measurement possible'.

To begin with, as Kfia (1993) makes clear, the ontological status of numbers is challenged, but whether or not they exist, the effect of the manipulation of a number representing some parameter is undeniably *real*. Again, there is an immanent structure to the discussion: in some scenario, a length of 10mm might be preferable to a length of 20mm; in others, the opposite will be true. Furthermore, all quantification is fraught with uncertainty and variability. *Uncertainty quantification* (the determination of the probability of certain outcomes given that some aspects of a system are not exactly known) is the science of quantitative characterisation and reduction of uncertainties in both computational and real-world applications; future studies could investigate how this field might be applied to the construction of AAAs. As with the parametrisation discussion, the *tolerance* of our measurements may be an important factor due to the inherent complexity of AAAs – needless to say, computer models set to redundant tolerance levels can be very expensive to evaluate.

iii) Implementation of constraints

In DeLanda (2010), a distinction is made between the terms 'variable' (the specification of an object's degrees of freedom) and 'parameter' (the specification of environmental factors that affect the object). As DeLanda explains, in some scenarios both terms can be mapped onto the same phenomenon: 'Temperature can be a variable, the internal temperature of a body of water, for instance, as well as a parameter quantifying the degree of temperature of the water's surroundings'. This distinction appears less important in the context of AAAs, for which the two terms can be viewed as interchangeable; what is important is the way in which the value of the parameter/variable (in data) *affects* (makes a difference to) and *effects* (brings about) something (a formal change with associated out data).

In AAA theory, these two verbs are typically linked: if a quantity of something exerts influence on our assemblage (as when a legal requirement is introduced that limits the height of our geometry), it somehow constrains it. This *affects* the properties and the degrees of freedom of our assemblage (making the ranges of its height and volume smaller, say), and creates an *effect* of some kind (visually shrinks the geometry). Noting the potentially constructive distinction between variable and parameter, we will henceforth follow the conventional nomenclature in contemporary architecture and use the term 'parameter' for any defined value with a capacity to affect/effect the assemblage.

As an architectural implementation of mathematical optimisation strategies, AAA translates architectural morphogenesis into the mathematical problem of finding the numerical minima (or maxima, or zeros) of an objective function limited by *constraints*. While in physics, constraints are limitations on the motion of a system (such as a particle), and in biology they are contingent causes exerted by specific structures or dynamics (such as an environment constraining the evolution of an organism), in an anticipatory adaptive assemblage, constraints are either explicitly defined (as parameters) or the result of implicitly limiting factors: bounded domains, finite ranges, bounds in the geometrical degrees of freedom as defined by the form seed, contingent constraints (such as when the potential geometric response associated with the minimum and maximum amount of annual solar radiation falling on a geometry is smaller than that geometry's morphological capacity to change), and or combinations of constraints (as in the case of two bounded domains acting together to limit the freedom of the geometry).

As Tschumi (2015) notes, architecture is filled with constraints. These constraints, these rules, these regulations (whether they are city regulations, budgets or other limits) are things we learn to deal with, to play with even. We must learn to make these constraints, dare i say, part of the project. Unless we make these limits pleasurable our lives as architects would be miserable. Much or architecture is a game where one simply takes advantage of the disadvantage, redefining the invisible opponent (the rule; the limit; the constraint) as a positive factor.

Constraints are conditions that restrict the 'motion' of the system by limiting its geometrical degrees of freedom by way of values. This is easily illustrated with an areal constraint (of, say, maximum 100m2) applied to a rectangular surface: if the length of one of its sides is 10m, the other side can be no longer than 10m. Constraints are thus contingent causes exerted by specific structures or dynamics. While it is required that hard constraints be satisfied (that is, while such constraints define the feasible set of candidate solutions), soft constraints are preferred but non-mandatory. Global constraints represent a specific relation on a number of variables taken together, and prescriptive constraints tell us 'not what to do but what to avoid doing'. As explained in Arora (2012), mathematicians use further types of constraints that might become valuable to the future development of AAAs, including equality constraints, inequality constraints, and integer constraints. The set of candidate solutions that satisfy all constraints is called the feasible set.

For attempts to maximise an objective function, typical constraints might involve time, money, and other resources (such as computational expense). The amounts of such constraints are not limitless, and their limits in turn limit (demarcate) the best possible value of the objective function. For attempts to minimise the objective function, constraints are likely to be more particular to the situation at hand. The use of AAA could conceivably yield the development of a parametric sensibility through material constraints – including the 'auxiliary loads' discussed in Paper IV and Paper V – that might in turn be viewed as an implicit critique of the disregard of material logic in many parametric approaches, which tend to create a disconnect between digital tools and material experience.

It is important to remember, in the light of the present discussion, that what these constraints actually constrain are *values*, that is, they demarcate the 'edges' or 'thresholds' or 'limits' of our axiological potential.

iv) Application of objectives

Closely related to the mathematical concept of a domain is that of a range. The range is the set of all possible output values (a variable commonly denoted as y) that results from using a particular function. In a AAA, ranges can be used as input or output data; the latter typically defines the possible value outcome (out data) of the parametric operations that the form seed is subjected to.

For axiological values to inform our architecture, they need to be translated into material capacities by way of quantification, as outlined in section 7.1(ii) above. The end result of such a quantification is a range, which may for instance be aesthetically or ethically defined ('the edge can rotate from 0 to 180° about its origin in the xy plane' or 'the test surfaces can achieve a daylight factor of 0-5 lux').

Determining an optimal, necessary, sufficient, satisficing, consensual, preferable, or critical value within such a range equals defining an objective for the transformation of the AAA. A detailed description of this taxonomy of terms is beyond the scope of this thesis, but they can be viewed as extensions of or reactions to the 'bounded rationality' concept proposed in Simon (1947), which was in turn a complement to the 'rationality as optimisation' approach to decision making preferred by most economists, which views decisions as fully rational processes of finding optimal choices given the available information. (For a technical discussion on bounded rationality, see Rubinstein (1998).) In brief, it may suffice to note here that the objective categories (or cognitive heuristics) above add to ideal optimality and the notion of 'satisficing,' introduced in Simon (1956), other possible strategies for selectively cropping a range to define an objective. We may hold a daylight factor of 5 lux to be optimal for a given test surface in a given situation, and 2 lux to be absolutely necessary for any work to be carried out in that space, but we may also view 3 lux as a sufficient illuminance level, or instruct the evolutionary solver to stop when it finds a satisficing option at 2.5 lux. A design team may need to reach a consensual value that represents the collective opinion. In a weighted definition, a multiplier may be used to promote solutions above a preferable value, and there might exist critical points above or below which solutions become more or less valuable to us.

Whether the daylight factor used as an example above is to be regarded as an 'ethical' or 'aesthetic' value, or whether it aligns with some other axiological field is to an extent a matter of context and personal opinion. Crucial to the function of these values in the context of AAAs is their capacity to link geometry to mechanisms of *anticipation*. The conditions described by these lux values are of course the result of a daylight factor simulation; an analysis carried out to test the *future* properties associated with the geometry, and to bring this value back (from the future) to inform the evaluation of design iterations (in the present). More precisely, a simulation of a simulation takes place: we define a virtual state of the form seed by 'simulating' a possible geometric configuration, then simulate the daylight factor that a test grid within this geometry would achieve. The use of objectives to constrain the optimisation process is a teleological operation: we assign extrinsic purposes to the assemblage, and essentially allow them to function as value-driven attractors for the geometrical transformations to follow. Objectives thus direct anticipation in AAAs.

v) Evolutionary evaluation

Natural selection acts in such a way as to maximise fitness. Evolutionary solvers mimic this behaviour. The mathematical definition of a AAA is a fitness function (formally a particular type of objective function), used to guide the simulations toward optimal design solutions. The genetic programming at the heart of AAA assigns a string of numbers to each design solution. This string awards a value of merit to the solution, indicating how close it came to meeting the stipulated specification. It may be referred to as the solution's *chromosome,* and it is generated by applying the fitness function to the simulation results obtained from the solution (phenotype) in question. A simple principle is then adopted: for each generation generated, the evolutionary engine deletes the n worst-performing design solutions, while breeding n new ones from the best-performing design solutions.

In other words, an *evaluation* is made of each generated individual solution, and the relative *fitness value* that this evaluation establishes drives the evolution of the entire assemblage towards its final actualisation. Again at this level, (numerical) values (quantifying axiological values) direct the development of the AAA form. While the computer performs the actual evaluation, the AD designs the fitness function (the AAA) that defines the evaluation premises. For the algorithm to converge on appropriate solutions (indeed to converge at all), the fitness function needs to be well designed.

As clearly illustrated in Simmons (2010), *adaptation* is key to survival in nature and to the mechanisms of evolution described above, which implicitly optimises organisms as well as AAAs. As is the case with its biological correlative, the evolutionary logic at the heart of AAA can feasibly turn such assemblages into a robust response to changing environments: detaching the AAA from one context and plugging it into another is highly likely to produce a change in form as the assemblage adapts to its new environment. Likewise, borrowing again from de Saussure (1916), we may consider the evolutionary operations at work inside the genetic algorithms that shape the AAAs to be *synchronically* adaptive (making adjustments to solve the present objective function), but also as being *diachronically* adaptive (making adjustments over time to become better at solving particular kinds of objective functions), as noted by Holland (1984):

> Genetics provides us with a canonical example of a complex search through a space of ill-defined possibilities. […] It is possible to give genetic processes an algorithmic formulation that makes them available as control procedures in a wide variety of situations. By using an appropriate production (rule-based) language, it is even possible to construct sophisticated models of cognition wherein the genetic algorithm, applied to the productions, provides the system with the means of learning from experience.

This was a potentially fertile and interesting area of study when Holland discussed it almost 40 years ago, and it is even more fertile and interesting today, when the technology has finally caught up with his thinking, though many of the difficulties (including high dimensionality) that attend complex and ill-defined problems remain. Evolutionary evaluation is the mechanism that directs adaptation in AAAs.

vi) Evaluative evolution

A final level of valuation occurs once the algorithm has run its course and produced an entire AAA species. The individuals within this species, subdivided into generations, all carry differing chromosome values. Selecting a final option is rarely as simple as sorting the list of chromosomes and picking the individual associated with the highest aggregated value, since the top position is likely to be shared by a substantial number of candidates (and the portion of the list holding individuals that meet a sufficient or satisficing level of objectives is likely to be even larger).

This is because multi-objective optimisation problems are by nature often *multi-modal* systems: they possess multiple (equally) good solutions. That is, there may be a considerable amount of solutions that are either globally good – different geometries achieving identical fitness values – or a mix of globally good and locally good solutions – different geometries achieving the same level of fitness through a combination of individual local values. Given objectives x and y, solutions A, B, and C may all reach the same fitness value score. But while A and B are globally homogeneous (both reaching the values x = 5 and y = 5), solution C is locally better at achieving the first objective (x = 8, y = 2).

Many strategies exist for how to evaluate the outcome of these evolutionary processes, including the use of Pareto fronts (the set of all Pareto-efficient allocations, a situation in which no preference criterion can be better off without making at least one individual or preference criterion worse off), or the tactic of converting the original problem with multiple objectives into a single-objective optimisation problem, thereby constructing what is known as a *scalarised* problem. Hwang & Masud (1979) divide the strategies for finding the most preferred results into four classes: 1) no preference methods (a neutral compromise solution is identified without preference information from a decision maker), 2) *a priori* methods (the best solution is found given preference information from the decision maker), 3) *a posteriori* methods (the decision maker chooses from a representative set of Pareto-optimal solutions), and 4) interactive methods (the decision maker is allowed to iteratively search for the most preferred solution).

Common to the three latter methods is of course the presence of a decision maker, which is assumed to exist in the generation of AAAs. (This is by no means a given: just as automated experimentation is a budding field demanding attention from future AAA researchers, so there is in principle no reason to assume that the AAA system cannot evolve into a fully automated process that, given a site and a brief, develops its own form seeds and outperforms human ADs.) Which method is eventually adopted is a matter of preference, but the most sophisticated application would probably err on the side of *a priori* methods, since this can arguably incorporate the representative set of Pareto-optimal solutions used by *a posteriori* methods, and appears more objective than interactive methods.

7.2 Immanent frames of probability

Having explained in some depth the six operations of valuation that control the development of AAA's, let us discuss the important connected notions of immanence and desire, before turning our attention to the underlying fields of ethics and aesthetics.

There is a 'subjective' or 'relativistic' aspect to the operations above that can be connected to what Smith (2012) calls Deleuze's (and Spinoza's, and Nietzsche's) 'ethics without morality'. A building is the product of a confluence of overlapping *frames* of reference, an intersection of what Deleuze would call 'planes of immanence'. This concept – which for Deleuze is equated with other theoretical inventions such as 'body without organs' (BwO), 'plateau,' and 'plane of consistency,' and 'desire' – is not easy to intuitively grasp. A full philosophical comprehension may also be redundant in terms of the present context (Gao (2013) provides a good introduction; Massumi (1992) a more in-depth discussion), but let us examine how it relates to AAA theory. A passage in Ballantyne (2007) might serve to begin to clarify this:

> Finding a form for a building has a parallel in finding form in oneself. One fixes a limit – a frame. I decide that I am the kind of person who does some things and who would never do some other things; and then at formative moments, I realize that I have to revise the idea and that I'm not quite (or not only) the person I had thought I was.

Cache (1995) – a disciple of Deleuze – goes one step further, noting that 'strictly speaking, architects design frames,' and that the frame

> reduces architecture to its most basic expression and allows us to formulate a concept that derives directly from Eugène Dupréel, whose philosophy was centred entirely on the notion of frame of probability. Dupréel criticized the classical causal scheme, remarking that no value has been attributed to the interval that separates the cause from the realization of its effect. For a cause to produce an effect, this interval must be filled. For in and of themselves, the set of causes that produce an effect are only frames of probability. […] this intercalar dimension of reality allows us to reformulate a rationalist theory of architectural practice. Architecture would be the art of introducing intervals in a territory in order to construct frames of probability.

An interesting precedent, in Dupréel (1933) the Belgian philosopher developed an ethical theory and a theory of knowledge deeply influenced by sociology, which have, it seems, yet to be properly introduced to the anglophone world. His frames of probability can be compared to the system-level constraints that produce emergent effects in assemblages, as illustrated by the discussion in Deacon (2012) on neuroscientist Roger Sperry's example in Sperry (1980) of a wheel that, although its component particles (atoms, molecules)

> are not changed individually or interactively by being in a wheel, because of the constraints on their relative mobility with respect to one another, they collectively have the property of being able to move across the ground in a very different pattern and subject to very different conditions than would be exhibited in any other configuration. The capacity to roll is only exhibited as a macroscopic collective property. It nevertheless has consequences for the component parts. It provides a means of displacement in space that would be unavailable otherwise.

As Deacon notes, being part of this whole 'indirectly changes some of the properties of the parts,' and that it 'creates some new possibilities by restricting others'. Sperry reads into this not just a trade-off between constraint and unprecedented collective properties, but an instance of *downward causation,* as being part of the whole alters the possible movement of its parts. This seems like a stretch if the term is used in its original meaning as introduced in Campbell (1974) (where the notion of 'causation' is suspended in evolutionary time across several reproductive generations), but what is present in Sperry's wheel are Dupréelean *frames of probability*. As Deacon explains

> Outside of their inclusion in a wheel, individual atoms are exceedingly unlikely to move by spiraling in the plane of forward movement; but inclusion in a wheel makes this highly likely. […] this configurational effect that the whole has on its parts might more accurately be described in terms of constraints. […] It's not that a given atom of the wheel cold not be moved in some other way, if, say, the wheel was broken and its parts scattered; it's just that rotational movement has become far more probable.

Being an assemblage, the wheel's properties are irreducible and immanent (irreducible as they emerge from atomic interactions but cannot be ascribed to any atomic property; immanent as the properties would cease to exist if the atomic interactions were terminated). But what is also immanent is the axiological status of the frames of probability.

Deleuze made a distinction between 'ethics' and 'morality'. Smith (2012) explains that while the latter is a set of constraints that 'consists in judging actions and intentions by relating them to universal or transcendent values ("this is good, that is evil"),' the former is, on the contrary, 'a set of "facilitative" *(facultative)* rules that evaluate what we do, say, and think according to the immanent mode of existence that it implies'.

'Mode of existence' is a Nietzschean figure of thought key to Deleuze's immanent position (Brassett (2017) is a design-related paper on this topic). As Smith (2012) goes on to explicate:

> Rather than judging actions and thoughts by appealing to transcendent or universal values, one evaluates them by determining the mode of existence that serves as their principle. A pluralistic method of explanation by immanent modes of existence is in this way made to replace the recourse to transcendent values; an immanent ethical difference (noble / base) is substituted for the transcendent moral opposition (Good / Evil).

That is, we should judge things by their own merit rather than by a universal standard. This seems like a reasonable attitude, but Smith does not shy away from the obvious follow-up question: 'How can one evaluate modes of existence using criteria that are immanent to the mode itself without thereby abandoning any basis for comparative evaluation?'

Deleuze's answer is: by something's immanent criteria of *capacity* (a term we of course recognise from the Ontology chapter above), or, again in Smith's concise interpretation, 'the manner in which it actively deploys its power by going to the limit of what it can do (or on the contrary, by the manner in which it is cut off from its power to act and is reduced to powerlessness)'. The ethical task, according to Deluze (1988), entails 'an amplification, an intensification, an elevation of power, an increase in dimensions, a gain in distinction'. Our anticipatory adaptive assemblages need to be evaluated according to the intensive criteria of their capacity to affect and be affected, and this evaluation is in itself not only critical but creative (part of the creation of the assemblage). As noted in Deleuze (1962):

> Evaluation is defined as the differential element of corresponding values, an element which is both critical and creative. Evaluations, in essence, are not values but ways of being, modes of existence of those who judge and evaluate, serving as principles for the values on the basis of which they judge.

To reiterate, the AAA can be viewed as a designed set of irreducible and immanent frames of reference that at any given point in time is associated with probabilities. These probabilities constrain and control the AAA's capacity to affect and be affected. The critical and creative evaluation of values (that restrict the system and that it aims to achieve) makes it possible to push the AAA towards reaching an optimal application of its immanent capacities, which amounts to an ethical act (enhancing its mode of existence). We shall return to the idea of creative evaluations of immanent capacities and their relation to complexity in section 7.9 below. For now, suffice to say that the capacities immanent to the (mechanics of the) form seed are explored by the genetic algorithm, and that what sets this process in motion is *desire*.

7.3 Desire

Deleuze & Guattari (1980) confusingly conflate several concepts by stating that

> The BwO is desire; it is that which one desires and by which one desires. And not only because it is the plane of consistency or the field of immanence of desire.

The AAA interpretation of this is not that the terms are synonymous, but that desire is the driving force that renders the other concepts possible. While the terms are related, desire is also not synonymous with 'objective'. Objectives are the quantified conditions desire reaches for, the axiological targets we aim our objective functions at. But desire is something else. Desire is the often elusive call to action, the axiological reason for creating AAAs in the first place. We can seek to understand how the world functions, how those functions can be intercepted and operated, and how such operations can produce knowledge (ontology, methodology, and epistemology, respectively) – and yet without an understanding of how desires drive that functioning, operation, and production we will not be capable of successfully creating and controlling a AAA.

Palmer (2008) draws our attention to the fact that the word 'desire' contains 'two possible antitheses: desire for and urge to. Both perspectives are parts of the genesis of architecture, the desire for creativity and the urge to possess'. A third meaning that features less prominently in dictionaries is that adopted by Deleuze & Guattari (1972): desire as the essential process of all life; desire as the driving force of what they call 'the desiring-machine'. Buchanan (2008) notes that the highly political thesis developed by Deleuze and Guattari in *Anti-Oedipus* – the first of the two volumes making up *Capitalism & Schizophrenia* (in the sequel, *A Thousand Plateaus,* they speak instead of abstract machines and assemblages) – boils down to a 'thesis [that] in a nutshell is that if we understand desire properly and distinguish it effectively from interest then the revolution *is already* made'.

Let us disregard the political overtones, and simply note that desire is a key concept in Deleuzean philosophy. While, as Gao (2013) points out, desire is usually understood as 'something abnormal, avaricious and excessive, the opposite of rationality, to be controlled and suppressed in man,' Deleuze's desire is 'much wider, referring not only to man, but also to animals, objects and social institutions,' and furthermore 'not a psychic existence, not lack, but an active and positive reality, an affirmative vital force' that has 'neither object, nor fixed subject. It is like labour in essence, productive and actualisable only through practice'.

Buchanan (2008) explains that the desiring-machine was the starting point of *Anti-Oedipus*, a concept invented by (the psychoanalyst) Guattari, which seems reasonable seeing that the concept is psychologically defined: 'the schizophrenic, in the full flight of delirium, reveals to us the true nature of desire as a synthetic process. The schizophrenic process, then, is Deleuze and Guattari's model of how desire works'. Schizophrenic delirium lays bare the material processes of the unconscious, and the authors' argument is that schizophrenic delirium takes the forms it does because the unconscious is 'machinic'. That is, the unconscious is *also* a machine, just as, in Deleuze and Guattari's view of the world in *Anti-Oedipus:*

> Everything is a machine. Celestial Machines, the stars or rainbows in the sky, alpine machines – all of them connected to those of his body. The continual whirr of machines.

This machine concept is precursive to their latter 'assemblages,' and so, a AAA can be viewed as a machine, fuelled by processes of desire: the desire for a better world, the urge to design and construct that world. This is AAA's *raison d'être:* to assemble desire. As Deleuze & Guattari (1980) state,

> there is no desire but assembling, assembled, desire. The rationality, the efficiency, of the assemblage does not exist without the passions the assemblage brings into play, without the desires that constitute it as much as it constitutes them.

The axiological/ontological mechanism is roughly this: an assemblage results from relations between components (including for instance axiological ideas and a malleable digital geometry), relations that affect and are affected by other relations and components in the assemblage and its environment. These flows of affect constrain (in Deleuze & Guattari's parlance 'territorialise') the assemblage's capacity to desire, that is, its performance and its potential for achievement.

7.4 Ethics: Surpassing the sustainable

The 'capacity to desire' may result in part from ethical considerations. Ethics is derived from the Greek word 'ethos,' meaning dwelling or habitat. But rather than referring to the ideological notion of 'habitus,' the emphasis here is on the *habit*, viewed not as a mere passive response to a stimulus, but as a creative power. As described in one of the major classics in this field, the Nicomachean Ethics (Aristotle 350 B.C.E), 'moral virtue comes about as a result of habit'. The AAA method offers mechanisms to institutionalise such moral virtues – individually defined by the AD – and to establish as a convention or norm (a habit) the explicit recognition of ethical considerations as axiological means of directing desire, thus establishing a direct and constructive link between ethical values and AAA production. This is echoed in Braidotti (2006), where the author wants to

> address the ethical temperature or fibre of our era, also known as the technologically driven historical phase of advanced capitalism. (…) the concern (is) that the desire for social justice and progressive transformation, which is one of the

salient manifestations of our ethical consciousness, seems to be dwindling today. Times are definitely no longer a-changing.

Some facts on the relationship between material culture and climate change should make it clear that in some respects, architecture is uniquely positioned to make our times become a-changing again. As shown in UNEP/IRP (2019), rapid growth in global materials extraction is now 'the chief culprit in climate change and biodiversity loss'. Human well-being has improved remarkably since the 1970s, a half-century when the world population doubled and the global gross domestic product grew fourfold, but the advance was fuelled by vast amounts of natural resources. Since 1970, operational energy (used primarily to heat, cool, and light our edifices) has, in the words of Benjamin (2017), 'declined as a percentage of total energy consumption in buildings,' while embodied energy (used to extract, manufacture, transport, and assemble materials into buildings) has rapidly increased.

Again according to UNEP/IRP (2019), the amount of materials extracted from nature has grown roughly ten-fold since 1900. Resource extraction has more than tripled since 1970, including a 45% increase in fossil fuel use. Extraction went from 27 Gt in 1970 to 92 Gt in 2017; the report projects that it might more than double to 190 Gt by 2060, while greenhouse gas emissions could increase by 43%. If we include the manufacturing of building materials – and these alarming figures certainly suggest we should – the construction and operation of buildings, as noted in IEA/UNEP (2018), account for between 35% and 40% of both global final energy use and worldwide energy-related CO_2 emissions.

Add to this Wang et al. (2005) and Castro-Lacouture et al. (2009), who conclude that the construction sector uses around 40% of all natural resources extracted in industrialised countries, while consuming almost 70% of electricity and 12% of potable water, and one immediate conclusion should be clear: decreasing global final energy use, CO_2 emissions, and other 'green' concerns are to a considerable extent tasks that need to be tackled by the AEC industry, with the support of political and commercial institutions. As a comparison, Lee et al. (2020) note that the much-derided global aviation industry (before the Covid-19 pandemic, which still appears to be raging at the time of writing) is responsible for around 3.5% of climate change caused by human activities, with two-thirds of the impact being attributed to non-carbon dioxide emissions and the rest from CO_2. In other words, our use of buildings is 11 times as detrimental to the climate as our use of airplanes. There is no doubt as to which culprit should be prioritised.

Another immediate conclusion is that aiming to *sustain* this situation will result in a continuing *depletion* of natural resources and *prevent* ecological recovery. Aiming for sustainability is no longer sustainable. The now commonplace meaning of that term, defined in the 'Brundtland report' WCED (1987) as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' is simply not enough. Rather than *sustainable* design, we need *surpassing* design, buildings that challenge the status quo and meet the needs of the present while *enhancing* the ability of future generations to meet their own needs, including the ability to survive. The ethical responsibility of forthcoming generations of architects and engineers will ultimately be measured against this standard. There are many ethical dimensions that can be applied to the built environment, but arguably no one is as pressing as the damage it inflicts on the environment. While AAA is no magic bullet, it seems clear that the reinterpretation of the desired result from a sustainable to a surpassing outcome will be an unfathomably hard task without the adoption of design processes based on optimisation strategies.

Rendering the underlying desires and values that drive and control the design of a building explicit would seem like a prudent first step along that trajectory. In Billington (1983), structural engineering is elevated into 'structural art' only when it pursues the finely alliterated triad of efficiency, economy, and elegance. But why stop there? Shouldn't architectural assemblages be hypersensitive to the fragile environments in which they are situated, to the cultural and technical 'spirit of the age,' as well as to their ethical environments, their contextual climate of ideas about how – and in what kinds of buildings, made from which materials, constructed according to what engineering logic – we should live? As ethical values are used to calibrate parameters within the AAA, the assemblage adapts to this contextual ethical environment while simultaneously adapting to the actual physical environment in which it is positioned, giving rise to a distinctive, value-based aesthetics.

7.5 Aesthetics: Form follows fitness

If the relationship between ethics and AAA is centrifugal in nature, drawing ethics 'into' the assemblage, the relationship between AAA and aesthetics is based on the opposite, centripetal, motion, effectively turning the assemblage into a direct manifestation of its underlying aesthetic structure. This is to be expected, as any final, actualised assemblage is nothing more and nothing less than a physical instantiation of the system of which it is a product. AAA emphatically refutes the claim in Scruton (1979) that there exists a 'distinction between architectural aesthetics and architectural theory': in AAA theory, the fundamentally ethical decision about what values should be manipulated produces the AAA itself (the building), while at the same time producing its (individual) theory, performance potential, and aesthetics. The final assemblage is thus brought into being in an immanent conformity with its underlying system. As Massumi (2002) notes, 'the subject (assemblage) does not express the system. It *is* an expression of the system'.

This observation reinforces the double articulation model discussed in section 4.6: the creation of a AAA defines the values that produce and constrain it, while the system's 'expression' (the second articulation) intrinsically adapts and extrinsically anticipates its performance metrics to produce a final, optimised individual, bringing the final assemblage into an immanent conformity with the system.

In Deleuze & Guattari (1991), philosophy, science, and art are shown to have different objectives and limits, making them irreducible to each other. Philosophy is concerned with the form of concepts, science with the function of knowledge, art with the force of sensation. 'Which is to say,' argues Zagala (2002), that

> *thought* is not co-extensive with *knowledge:* philosophy thinks with concepts, science thinks with functions, and art *thinks* with sensations. These different planes of practice interfere with each other, producing frames and interfaces which connect

> them. For example, philosophers create concepts of sensation, just as artists create pure sensations of concepts (as in the work of certain abstract painters like Mondrian and Malevich). But art does not *need* concepts in order to think.

It is arguably uncertain whether if this argument can be applied to the entire endeavour we refer to as art: considering the theory and method of an artist like Sol Lewitt, as described for instance in Lewitt (1967), will make it obvious that some art does need concepts in order to think, or rather in order to exist at all. But this is not the point.

Rather, as Deleuze and Guattari argue, the point is that an artist can for instance borrow a concept from philosophy not to prop up an art object (thereby unnecessarily subordinating it to another plane of activity), but to translate it into a sensation. What artists essentially create, according to this view, are blocks of sensation, and, as the argument is summarised in Deleuze & Guattari (1991), 'the only law of creation is that the compound must stand up on its own'. Analogous to this discussion on the processes and outputs of irreducible fields, AAA holds that architecture and engineering is concerned with the *impact of space* – that architecture creates spaces of concepts and sensations. Architecture thinks with space.

The conservative emphasis that Deleuze and Guattari place on the independence of art, the apparent lack of transversality between the planes of practice, is at first highly surprising given their focus on how component relationships form assemblages. But Zagala shows that this is a tactic to promote the autonomy of each field, divorcing the arts, for instance, from 'a direct embeddedment in definite social functions and [contextualising them] as valuable cultural commodities worthy of accumulation in themselves'. This line of thought leads to the idea of *novelty* becoming 'a constitutive requirement for cultural production,' as a demand for 'originality in modern art replaces the respect for origins in pre-modern art'. For Deleuze and Guattari, writes Zagala, 'the "new" is not simply the negation of something already known, but an encounter with something unthought'. Writes Deleuze (1968):

> the new – in other words, difference – calls forth forces in thought which are not the forces of recognition, today or tomorrow, but the powers of a completely other model, from an unrecognized and unrecognizable terra incognita.

These ideas appear to provide an embryonic armature upon which to construct an aesthetic for AAA, a value-based, population-driven, morphogenetic aesthetic of progressive and unpredictable differentiation. Following O'Sullivan and Zpeke (2008), it can be noted that architecture, and philosophy for that matter, begins with *difference,* with the production of the new, and that 'the new is an outside that exists *within this world,* and as such it must be constructed'.

This construction of the outside that exists within this world – Deleuze's 'unrecognized and unrecognizable terra incognita' – is the end goal of AAA. Through the value-based, population-driven, morphogenetic mechanisms already described, which produce assemblages by way of evolutionary solvers and genetic algorithms, two forms of differences are produced. As Trummer (2011) explains in a discussion of the concept of 'population thinking' found in Mayr (1963):

> One states that each individual has to be different from the other, but at the same time these differences among individuals sustain its difference as a species. The diversity of the individuals is critical to the entire species. And this is the reason why it is called population thinking. It needs a critical mass of different individuals in order to diversify its gene pool.

The AAA methodology provides this critical mass in the form of variations of the form seed and its attributes (associated data), in a direct analogy to the morphogenetic processes found in nature. As Mayr (2002) notes, the genetic material (comparable to the combinations of parameter settings in a AAA)

> controls the production of the body of an organism (assemblage) and all of its attributes, the phenotype. This phenotype is the result of the interaction of the genotype with the environment during development.

Trummer notes, following Strickberger (2000), that skeletal structures in various tetrapods (animals with four pods or feet) preserve homologies across evolutionary time, despite changes in size, shape, and function. The fact that the human hand, whale fin, and bat wing are all constructed on the same five-digit pattern should be enough to silence once and for all the tired and endlessly repeated adage proposed in Sullivan (1896) (and more or less hailed as a universal truth ever since) that 'form follows function'. Form does not follow function. Form follows an *objective* function. Form follows fitness.

This is made explicit in AAA structures, which, to apply Deleuze and Guattari's organisation of planes of practice mentioned above, 'thinks' through the creation of a population of spaces that simultaneously produce internal (individualising) differences between the singularities produced within the confines of a form seed and external (unifying) difference versus the formal potentials of other form seeds. While this AAA schema of spatial ideas or architectural concepts being developed from within a distribution of singularities exposes the phenotypes (virtual assemblages) to evolutionary pressures, the genotypes (the form seeds, in which the hereditary instructions are stored) remain unexposed. This makes AAA a *morphogenetic* process.

This morphogenesis sees values yield populations that 'unfold' the final form through what DeLanda (2002b) calls 'progressive differentiation'. In AAA, this differentiation is shrouded in a beneficial mist of complexity, as multiple parameters are simultaneously adjusted with the aim of achieving optimal compromises between multiple objectives, turning the design process into a truly explorative operation. The form seed is a compass, not a map: it points to possible areas of investigation, but those areas are firmly grounded in the Deleuzean *terra incognita*. This is the 'unpredictable differentiation' part of our definition of the AAA aesthetic, a strategic exploration of the dynamic and experimental realm of space. As explained by Guattari (1993), 'aesthetics isn't something that gives you recipes to make a work of art', but a 'speculative cartography' of 'forms that construct coordinates of existence at the same time as they live them'.

This seemingly abstract notion can be dismantled and used as a summary of the AAA aesthetic, a move that, on second thought, *does* turn the form seed into a cartographic device. But rather than a map, the form seed corresponds to the map *being drawn,* that is, to the very action of drawing the map. Having designed the form seed and defined the objectives, the designer relinquishes control over the exploratory part of the design process to the computer, which essentially draws the map of the design space (the fitness landscape) as it constructs new assemblages positioned within it. This 'cartography' is highly speculative in that the final forms are beyond prediction. We do not know where we will end up, because there is not even a map for the territory we traverse. Here be dragons.

It may be noted here that Gordon Pask, in the same Foreword to John Frazer's book that was quoted in section 2.5 above, is patently wrong about one thing. In this introduction, Pask (1995), the brilliant author, inventor, educational theorist, cybernetician, and psychologist, states that

> Whilst computer-aided architectural design is useful if repetition or standard transformations are required, it is inadequate to the task of producing new forms.

This may have been true 25 years ago – though even this is unlikely: this was 38 years after the first commercial numerical-control programming system (PRONTO) saw the light of day, 32 years after the release of the first commercially available CAD program (DAC-1); 26 years after the first SIGGRAPH conference; 14 years after the introduction of CATIA; and one year after AutoCAD R13 made the famous Autodesk program 3D compatible – but it is almost the opposite of true today. This particular Pask quote has not aged well; it is far more likely that today's 'new forms' will arise from the controlled-yet-serendipitous evolutionary processes of AAAs than that they will result from some spur-of-the-moment flash of divine inspiration.

While the end result of such controlled serendipity is typically an actualised AAA, the underlying aesthetic can in no way be reduced to a theory of the final assemblage (the building) per se. Notions of 'beauty' follow the two types of difference, internal and external, produced by the population of virtual assemblages, so that the most 'aesthetically pleasing' buildings become those that embody the quality of 'standing out' from other species as well as from other individuals within its own species: a mathematically-controlled (though not AAA-based) building such as Preston Scott Cohen's 2011 Herta and Paul Amir Building in Tel Aviv seems to be *Away from the flock* in the same way that the formaldehyde-suspended sheep in Damien Hirst's famous art work of that title is (Figure 15). Rather than evaluating singular individuals, the AAA aesthetic is concerned with studying and developing the dynamic of spatial assemblages, architectural forms that are by definition *presilient* and *postponist* – two neologisms invented by this author that we shall explore in further detail in the Discussion chapter to follow.

To conclude this chapter, let us again consider the connection between AAA aesthetics and the conceptual art of Sol Lewitt. In the seminal Lewitt (1967), the artist introduces the kind of art in which he is involved as 'conceptual,' noting that

> In conceptual art the idea or concept is the most important aspect of the work. When an artist uses a conceptual form of art, it means that all of the planning and decisions are made beforehand and the execution is a perfunctory affair. The idea becomes a machine that makes the art.

Figure 15: A mathematically-controlled (though not AAA-based) building such as Preston Scott Cohen's 2011 Herta and Paul Amir Building in Tel Aviv seems to be displaced or astray from the species it belongs to, just as the formaldehyde-suspended sheep in Damien Hirst's famous Away from the flock work of art seems to have run away. (Damien Hirst/Amit Geron)

While we are not endorsing a careless execution of actualised works of AAA architecture, this definition does seem to capture the essence of the aesthetic we are trying to expound, one that meticulously constructs an architecture-making machine out of ideas (geometries, constraints, desires, and so on – that is, out of *values)*. The analogy is not perfect: later in his essay, Lewitt proposes that conceptual art is 'purposeless,' and AAAs are certainly based on purposes, but some of Lewitt's ideas could have been written for AAA's aesthetic manifesto:

> It is the objective of the artist who is concerned with conceptual art to make his work mentally interesting to the spectator, and therefore usually he would want it to become emotionally dry. There is no reason to suppose, however, that the conceptual artist is out to bore the viewer. It is only the expectation of an emotional kick, to which one conditioned to expressionist art is accustomed, that would deter the viewer from perceiving this art. […] The ideas need not be complex. Most ideas that are successful are ludicrously simple. Successful ideas generally have the appearance of simplicity because they seem inevitable. In terms of ideas the artist is free even to surprise himself. Ideas are discovered by intuition. What the work of art looks like isn't too important. It has to look like something if it has physical form. No matter what form it may finally have it must begin with an idea.

Adhering to these remarks could make AAA an effective antidote to the prevailing adherence to dogmas of *style* within another contemporary project that seeks to combine theory and practice within a parametric framework. Schumacher (2011) claims that the 'theory of architectural autopoiesis identifies the pervasive phenomenon of architectural styles as […] relevant communication structures' for the 'new global style' for architecture and urban design that he calls Parametricism.

Schumacher's insistence that architecture's 'adaptive evolution progresses via the historical succession of styles' appears to be diametrically opposed to the AAA position, introduced already in Paper I, that form follows fitness. If AAA has a style – which is most likely not the case – then this style is characterised by its being *constructed from elements of surprise.* The ‘brute force’ instantiation of an entire design space is not very interesting from an aesthetic point of view, and not necessarily valid from an ethical position (as if the objective function can be solved by brute force, the design probably is not complex enough). Rather, it is the interactive nature of the design process, the fact that the AD sets in motion unpredictable trajectories within the design space and then allows herself to be surprised by the resulting phenotypes (this mechanism can be viewed as the ‘intuition’ of the system itself, by way of which, to stay with the LeWitt quote above, ideas are discovered) that produces what may be called a certain kind of value-based *beauty* as ethics become aesthetics and vice versa. While diverse combinations of conditions and constraints – historical, cultural, material, technological – will always define any built (or even designed) works of architecture and situate them within their respective circumstances, the *geometries* produced as AAAs can push the boundaries of these restrictions in unforeseen and productive ways. We may call this AAAs *principle of surprise,* and note that it is proportional to the level of complexity in the design: the more dimensions that are added to a MOO, the greater the chance that the resulting phenotypes will surprise us in constructive, beneficial, interesting ways.

What Schumacher seems to be aiming for is an explanation of why *similar* forms arise (or should arise) from his design method, a scheme akin to DeLanda’s ‘diagrams’ of ‘universal singularities’ shared by many assemblages (meant to replace the taxonomic function of the genus) with ‘style’ as the organisational device. As with DeLanda’s invention (discussed in section 3.7(iv) above), this seems like a convoluted way to, as Schumacher puts it, provide ‘a functional explanation, ie, an explication of the rationality of the phenomenon of styles in terms of its contribution to architecture’s ability to perform its societal function’.

Echoing the response in Kleinherenbrink (2019) to DeLanda’s conjecture, we may ask why on earth we need the construct of *styles* to do this work? Is the idea of adhering to a specific ‘style’ in architecture – be it post-modernism, troglodytism, or parametricism – not simply redundant?

AAA certainly holds this to be the case. While it may conceivably be argued that the design of a form seed takes place within the context of a ‘style’ that the AD can never break away from (what Schumacher calls ‘the inescapability of the formal a priori’), this amounts to a sort of design solipsism, an imprisonment in the idea that no transgression is possible, that nothing can be known about and that perhaps nothing exists outside of the ‘style’ one is working in. This seems restrictive and counterproductive.

Furthermore, the notion of a ‘style’ is fundamentally at odds with the principle of surprise. Stealing a quote used by Schumacher, Wiegmann (1829) notes that ‘only what is already known can be prescribed; an original work is born unassisted’. This image is so apt that it ought to be made into a technical term: the ‘unassisted birth’ of a AAA is precisely what happens when on a Friday night the AD leaves the computer in her office to spit out a few hundred thousand phenotypes for Monday morning. No one speaks of giving birth to a certain ‘style’ of a human baby. As LeWitt noted, what the work of art looks like isn’t too important. We just tick the boxes that can be ticked (find a suitable partner, take prenatal classes, move to an area with good schools) and hope for the best. Following the principle of surprise, the only thing we can be sure of is that the form to emerge will follow fitness.

DISCUSSION

8. DISCUSSION

Let us open this penultimate chapter by briefly touching upon a curious assemblage at the intersection of linguistics and anthropology: the Amerindian language Aymara. In most documented languages, the spatial conceptualisations of time perceive future events as lying *ahead,* with the experiencer *facing* the flow of events. The Aymara language – spoken in the Andean highlands of western Bolivia, southeastern Peru, and northern Chile – presents a fascinating contrast to this pattern. In Aymara, the basic word for 'front' *(nayra,* meaning 'eye/front/sight') also carries the meaning 'past,' while the basic word for 'back' *(qhipa,* 'back/behind') also carries the meaning 'future'. In an in-depth study, Núñez & Sweetser (2006) propose that Aymara speakers, at least the elderly, monolingual ones, metaphorically face the past as they travel back-first into the future. Apparently, these unusual spatial construals of time are connected to the significance Aymara speakers place on whether or not an event or action has been *observed:* the future is unseen, while the present and the past are visible, and so the unknown future is behind the speaker's field of vision.

If for the sake of argument we accept this line of reasoning and adopt the Aymara model by reorienting our thinking so that the past stretches out in front of us, we may humbly recognise that indeed we do know nothing about the future, and instead of trying to project what is to come, we can focus on organising what we do know. As we have seen, the past ahead is filled with some 13,000 years of genetic studies since the first human intervention in the sexual reproduction of animals or plants, with three and a half decades of assemblage theory, with an increased understanding of the role of building materials in the mechanisms of climate change, with the development of genetic algorithms and evolutionary computing, and with their introduction to avant-garde architecture which, as Carpo (2013) shows, roughly coincided with the first digital turn in architecture.

But we also see quite clearly, as they are closer in our visual field, recent developments that seem to suggest a highly promising future for AAAs, which are of course tempting to examine. Will anticipatory simulations, assemblage thinking, and evolutionary computation strategies be future architecture tools equivalent to yesteryear's prevalent straightedges, compasses, and drafting tables? Will ADs be expected to design hundreds of thousands of proposals for each and every client meeting? Will material properties and capacities be awarded an amount of agency in the design of the built environment?

This chapter makes a connection to Caldas (2001), before discussing AAA's connection to big data, introducing the neologisms presilience and postponism, exploring AAA's PlusEnergy potential, and subjecting the theory put forward in these pages to a 'hyperbolic test'.

8.1 Frozen accidents

If that is the goal, then the way to get there appears to be lined with intellectual curiosity, genre-defying interdisciplinary collaborations, and technological advances. In an introductory note to her far-sighted PhD thesis, Caldas (2001) explains the motivation behind bridging the perceived gap between disciplines that 'too often stay within the limits of their own paradigms, both in academic and professional realms'. The incorporation of evolutionary systems and adaptation paradigms within the architectural design process is presented as a strategy for disrupting this state of affairs, with the adaptation directed 'towards environmental behavior, looking for shapes that harvest daylighting and reduce thermal exchanges with the external environment'. Caldas uses a sort of pseudo equation to express the final model for how such an adaptive paradigm might become a part of architectural design methods:

> initial rules + randomness + adaptation [reaction + action | behavior] + frozen accidents

Untangling this equation reveals that the 'initial rules' are essentially the parametric nature of the form seed and its constraints (bearing in mind that this work was carried out before digital parametric design tools became readily available). Caldas quotes Holland (1975) to explain that randomness is the 'major driving force in mechanisms of adaptation such as those present in several natural and artificial systems,' achieved by Caldas through the use of genetic algorithms that allow stochastic and non-deterministic processes to perturb the system. The [reaction + action | behavior] part is derived from Popper (1992) and Holland (1992, 1995) respectively. 'Frozen accidents,' finally, is an idea from theoretical physicist Murray Gell-Mann, who in Gell-Mann (1995) defines it thus: 'Most single accidents make very little difference to the future, but others may have widespread ramifications, many diverse consequences all traceable to one chance event that could have turned out differently. Those we call frozen accidents'. A similar concept developed much later but perhaps described more eloquently from a philosophical point of view, and with particular focus on when in the life cycle of a process the 'frozen accidents' (or 'symbioses,' as he calls them) are statistically likely to happen can be found in Harman (2016b).

The equation amounts to a sort of condensed manifesto for Caldas's branch of evolutionary and adaptive architecture. For the frozen accidents to happen, however – as she must have been acutely aware when working with architectural multi-objective optimisation challenges in an era that predated now-omnipresent applications such as Grasshopper and Revit – calls for resources including (beyond substantial amounts of time to wait for evolutionary solvers to run the algorithms) the necessary technological infrastructure to be able to pragmatically implement one's ideas and turn theory into practice.

Invisibility is the hallmark of any successful technology. Weaving themselves into the fabric of everyday life, the most profound technologies end up becoming indistinguishable from it. Writing, probably one of the first information technologies, freed information from the limits of individual memory and became ubiquitous in all industrialised parts of the world. As Weiser (1991) points out, it is difficult to imagine modern life in the absence of text. Will it be difficult in the future to imagine an architectural design in the absence of AAA?

When Weiser wrote his piece, three decades ago, the argument was that silicon-based information technologies were 'far from having become part of the environment'. This is obviously no longer the case. Future historians and anthropologists will have no problem dating photographs as having been taken before or after 9 January 2007, when the first iPhone was announced. According to Costello (2019), the latest public sales figures released by Apple stated that 2.2 billion devices had been sold up until 1 November 2018 (Apple's share of the total market is crudely estimated to be between 20% and 40%). The handheld computer known as the mobile phone has become so omnipresent as to almost be invisible.

But as William Gibson once (or, as Quote Investigator (2012) insists, several times) said, the future is unevenly distributed. It wouldn't be entirely wrong to state that the technology has finally caught up with Caldas's vision, but it would be equally correct to point out that we are still nowhere near a situation in which the use of evolutionary computation has become commonplace in architecture. While future projections are always precarious at best (and bearing the Aymara model of the unseen future in mind), it wouldn't be surprising if evolutionary computation *did* become an all-pervasive technology in the AEC field, for three reasons: 1) it is potentially disruptive in the original Christensen (1997) sense of being able to create a new market with an associated value network, 2) it allows for the introduction of presilient and postponist mechanisms, discussed below, and 3) it aligns well with other promising technologies, such as the budding fields of automated research and big data. In the rest of this chapter we will review these connections to see how they might impact the future of AAA.

8.2 Big data

The Aymara perspective shines a light on recent developments in the field of computer science. In the mid-1990s, John Mashey was the chief scientist at Silicon Graphics, a trendy Silicon Valley computer graphics company delivering jaw-dropping special effects to Hollywood productions, as well as video surveillance systems to spy agencies. As suggested in Lohr (2013) and Diebold (2019) Mashey also, quite possibly, invented the term 'big data'.

In a review of the promises and challenges of big data, Hilbert (2016) argues that its 'impact on the social sciences can be compared to the impact of the invention of the telescope for astronomy and the invention of the microscope for biology'. He then goes on to compare our present-day version of big data with early examples of mass-scale computing such as 'the 1890 punched card-based US Census that processed some 15 million individual records,' and finds that the 'velocity, volume and variety of data' has increased exponentially due to improved bandwidths, data storage systems, and computational capacities.

In Carpo (2017) a meticulous yet speculative theoretical examination of the potentials of big data is carried out, in which it is suggested that this increase in data velocity, volume, and variety inevitably leads to a redefinition of scientific methodologies from a phase during which equations yield predictions to one during which precedents are retrieved and/or simulated. Before the advent of big data, scientists typically compressed collated generalised and formalised facts into a theory to produce a mathematical formula that could, as Carpo writes, 'predict similar events when similarly describable'. In a post-big data world, predictions are instead based on computation, used to 'simulate as many fictional precedents as needed when no actual one is on record'. Carpo uses an engineering example to drive home his message: if we imagine that 'we live in an ideal big data world, where we can collect an almost infinite amount of data […] at almost no cost […] we could assume that […] the experiential breaking of every beam that ever broke, could be notated, measured, and recorded,' then for most future events 'we could expect to find and retrieve a precedent, and the account of that past event would allow us to predict a forthcoming one – without any mathematical formula, function, or calculation'.

A plausible development along similar lines would be to set up simulations that generate the (big) data needed to optimise architectural structures for multiple objectives, such as (for instance) the continual tug-of-war between material cost and global warming potential. A frustration with the general lack of comparative tools of analysis charting such relationships lay behind the development, in Paper IV, of 'material phase transition' diagrams that can be used to predict which material system(s) will be most beneficial given a range of predefined objectives.

AAAs and PETs could be used to explore evolutionary designs through organised architectural science experiments while amassing vast libraries of big data. While we may not know today exactly to which use this data may be put, we can still begin to collect it while working out the details of its potential applications. While this may at first appear counter-intuitive, it is in fact a hallmark of the scientific method. It took thousands of years of measurements by astronomers from the Chaldean, Indian, Persian, Greek, Arabic, and European traditions to fully record the motion of our own planet, none of which was carried out with the specific aim of allowing Newton to include the measurements into consequences of his laws of motion. A connection between building materials science and this role of big data in the evolution of engineering is described in Carpo (2017):

> Artisan masons of old (and few survive in the so-called industrialized countries) knew very well how to make concrete on site the smart way, making it stronger, for example, in the angles and corner walls (more cement), cheaper in some infill (more rubble), thinner and more polished next to some openings (more sand), etc. But for engineers, concrete had to be dumb, homogenous, and standard, the same all over, because that was the only material they could design with the notational and mathematical tools at their disposal.

Thus concrete became a homogenous and 'dumb' material. But present-day technologies give it a new lease of life:

> ...variable property materials can now be designed and fabricated at previously unimagined levels of resolution, including concrete, which can be extruded and laid by nozzles on robotic arms, so each volumetric unit of material can be made different from all others. This is what artisanal concrete always was – which always scared engineers to death, because they could not design and calculate that. Today we can.

So processes that we associate with advanced contemporary engineering – the production of big data, complex simulations, experimentation that demands great computing capacities, and so on – help us move from the simplifications of standardisation-eager engineers to the expertise of artisans. We have come full circle. This example highlights one of the (many) potential ways to leverage PETs: use them to test highly specific manufacturing methods using materials with variable properties, and compare how such building elements perform compared to their 'dumb' predecessors. The connection between such a methodological-epistemic process and the 'new protocols [that] could spawn mass-customised building materials' proposed in Paper III seems obvious.

8.3 Presilience

Can our Aymara view of the past help us find other ways of leveraging the PET-based aspects of AAAs? Maybe reviewing an idea that has been remarkably successful in recent years will suggest ways forward. A concept fraught with conflict and contradiction, the trajectory of the term *resilience* through the scientific, legal, humanities, and political spheres has seen the concept pass from its beginnings in mechanics via ecology to psychology, get adopted by social research and sustainability science, only to become applied – perhaps inevitably – to the fields of architecture, engineering, and urbanism. It comes as no surprise, then, that Alexander (2013) notes there are highly divergent views of what 'resilience' actually means.

The mechanical definition of the term can be summarised as the capacity of a material to absorb energy when deformed elastically and to return it when unloaded, much like a balloon. Resilience, explains Ennos (2012), is the 'percentage of energy released by a material' as it is 'stretched to a point before yield occurs and then allowed to return to its rest length'. Pelleg (2012) opts for an even briefer definition: the 'maximum energy per unit volume that can be elastically stored'.

As noted by Petrillo & Prosperi (2011), two additional metaphors are even more dominant in contemporary resilience theories than this balloon parable: those of sand piles and controlled burning. In Bak et al. (1987), theoretical physicist Per Bak coined the expression 'self-organized criticality': as grains of sand are added to a pile one at a time, the structure is driven to the edge of instability, and eventually reaches a critical state as the stability is challenged enough to modify the state of the pile through an avalanche of sand grains. At this literal tipping point, the previous structure is no longer resilient. The controlled burning metaphor, meanwhile, describes a regenerative maintenance strategy, in which controlled combustion is used to reduce the build up of fuel that might otherwise result in larger and more serious wildfires. Such prescribed burning also stimulates the regeneration of the forest environment. Translated into the context of urban resilience, this analogy might for instance apply when actions are taken to regenerate spatial structures within the city fabric, such as through the demolition of an abandoned public housing project that clears the way for a new multipurpose structure. As shown in Regos et al. (2016), at times, a fire might even increase the biodiversity index of the burnt area. So should we 'prescribe' traumatic events in the hope that they might make our buildings and cities stronger?

Maybe not. But we could add the preparatory principle of anticipation as a part of the design procedure, and allow AAAs to simulate potential future actions and counteractions in order to optimise their structure, composition, and materiality based on predictions, expectations, and beliefs about possible future events. *Presilience* is essentially resilience with added anticipation, a way of countering more gradual and slower events or developments, such as, for instance, a sustained resistance to the inconsiderate applications of building materials that are detrimental to urban improvement in the long run, or an adjustment to future weather scenarios in the wake of climate change projections.

Zamenopoulos & Alexiou (2005) single out theoretical biologist Robert Rosen as the father of the contemporary notion of anticipatory systems. In his seminal treatise on the topic, Rosen (1985) attempts to understand and explain the nature of life itself through an examination of the role anticipation plays in its supporting processes, arguing (prior to later theorists such as Terrence Deacon) that the Aristotelian logic of 'final cause' – the 'end reason' answer to the fourth and last of Aristotle's questions that seek to explain why something exists – has been lost to science as a mode of explanation since it represents a violation of the traditional notion of scientific causality, which states that 'in any law governing a natural system, it is forbidden to allow present change of state to depend upon future states'. Rosen argues that such a finality is the only explanation for anticipatory behaviour, which is clearly present in biological systems, from the molecular to the human level. Furthermore, according to Rosen, such predictive models are fundamental scientific strategies pivotal to familiar actions such as planning and making decisions.

An anticipatory system, according to Rosen, contains 'a predictive model of itself and/or of its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a later instant'. That is, he envisages a dynamical system running in real time, coupled with a second dynamical system (a model of the first) that can run faster than real time, thus rendering it capable of predicting future behaviour. Generally speaking, such predictions cannot be perfect. The discrepancy between the actual (system) and predicted (model) behaviour corresponds to that of an open and a closed system (as discussed in section 2.7). The concept establishes relations between a natural system (the weather conditions on a particular building site, say) and a formal system (for instance the instructions used to design a building on a computer), consistently encoding the former into the latter. Presilience in AAA is the proactive act of anticipating and preparing for potential future stresses and disturbances, a kind of preemptive resilience strategy. This principle is at work in all papers, but is perhaps more prominently positioned in Paper II, Paper III, and Paper V (while bearing in mind that the auxiliary loads and MPT diagrams introduced in Paper IV essentially comprise a tool for presilience).

8.4 Postponism

Just as presilience is based on anticipation, *postponism* is related to adaptation. More specifically, it is based on a particular kind of adaptation: the kind that mirrors the reciprocal relationship between resources and results. While the available resources always limit the expanse of the design space, the postponist mechanism adapts the results to the resources at hand by stretching the combined analysis and search processes to their very limit.

The notion of postponism is based on the contemporary observation that technological progress supports and accelerates humanity's increasing desire to postpone decision-making processes, a reflection that will be perfectly obvious to anyone who has lived through the death of the phone booth, the dragonfly life of beepers, the near-total ubiquity of mobile phones, and the ensuing I'll-call-you-when-I-get-there mentality of their owners.

If we believe in basing our decisions on knowledge factors (as opposed to some variation on the theme of 'gut feelings'), postponism – the systemic deferral of action to the last possible moment – makes perfect sense, since collecting as many of those factors as possible should provide for more informed decisions. Treating knowledge as a potential that increases with each phenotype adds value to the time leading up to the point when a final decision has to be made. In AAA, this corresponds to the *actualisation,* as a final proposal or a built construction, of a virtual design iteration. Only after such a 'freezing' of the parametric digital design does the exploratory process stop and the actual manufacturing begin.

The more developed the system, and the more developed our intuition for working the system, the more we can push back that point of no return, gathering until the very last moment as many virtual AAAs, as much information about our design and the potential of our design space, as possible.

Historically, the simplest decision model has of course been one with only two alternatives. As explained in McCormack et al. (2004), this concept of duality, the division of everything in the world into discrete either/or functions, is known as *manichaeism*. It was allegedly adapted by Zarathustra and then incorporated into many other organised religions. Today, however, the black-and-white duality concept seems less than adequate at describing and understanding a world that, as our understanding of it expands, appears to increasingly lack real opposites. Instead of a flipping a metaphorical coin, we choose to compute as much data as we can and make an informed decision between as many alternatives as possible.

There is a difference between a decision and an objective: a good decision is the process of optimally achieving a given objective. As a bad decision early on within the design process might force us to make more bad decisions further down the line, we wait for as long as possible whenever the problem at stake contains unknown parameters. If the first button of one's coat is wrongly buttoned, all the rest will become crooked. This is yet another reason why our postponist and presilient AAA system will be more efficient if put to use during the early phases of a design, at the time when those decisions matter the most.

Postponing commitment not only provides the AAA system with more valuable time to collect, run, investigate, scrutinise, and evaluate parameters and simulations – it also extends the decision-making process itself, that is, the contemplation of the elements to be decided upon. This might provide opportunities to reconsider decisions associated with the structure being designed and the material flows it produces, consumes, and supports. Using the mechanisms of presilience and postponism, those flows can be optimised so as to attain the (axiological) end goal of our study of AAAs.

8.5 Power plants for living in

Just as we thought our Aymara viewpoint had let us arrive at an understanding of the world as being fundamentally composed of assemblages, Manuel DeLanda decides to shake things up. 'In a very real sense,' he writes in DeLanda (1997), 'reality is a single matter-energy undergoing phase transitions of various kinds, with each new layer of accumulated "stuff" simply enriching the reservoir of nonlinear dynamics and nonlinear combinatorics available for the generation of novel structures and processes'.

Now, what are we to make of this? In DeLanda (1992), the philosopher pointed out that as opposed to 'conservative' physical systems (that are essentially isolated from their surroundings), 'most systems in nature are subject to flows of matter and energy that continuously move through them'. Returning to the idea in DeLanda & Harman (2017), DeLanda provides a time-related explanation of the concept, noting that 'a mind-independent reality possesses a variety of significant *time scales*,' and that across 'very long time scales […] many objects disappear from view and you would only be able to "see" flows, that is, becomings'. As Van der Tuin & Dolphijn (2010) assert, DeLanda is faithfully following the work of Deleuze and Guattari here, drawing on their concept of an 'abstract machine' that 'captures processes without form or substance that can be found in concrete assemblages of biology, sociology, and geology alike' to offer a rethinking of the dualities of transcendental humanist thought, including causal structures and teleology. DeLanda (1996) develops the theme further:

> This conception of very specific abstract machines governing a variety of structure-generating processes […] points towards a new form of materialist philosophy in which raw matter-energy through a variety of self-organizing processes and an intense power of morphogenesis, generates all the structures that surround us. Furthermore, the structures generated cease to be the primary reality, and matter-energy flows now acquire this special status.

We can theorise our built environment as being the result of a series of such abstract machines generating matter-energy phase transitions; architectural structures considered as a series of temporary solidifications within a continuous flux of energy-matter flows. Just as common materials transition between states (solid, liquid, gaseous, plasma) as a result of a change in some external condition (temperature, pressure, etc), so a building material – steel, say – can transition not only physically (from solid to liquid state through melting in a fire, for example) but also conceptually and contextually, from its original raw state of being (mainly) iron and carbon via becoming mined and processed into a building component through to being transformed into the envelope of a building and part of a city, only to be recycled or scrapped following the building's demolition. Building materials thus flow through space and time, in and out of assemblages, merging temporarily into man-made structures that are made of various temporary material compositions, accretions, alloys…

The shifting trajectories of this flow of energy-matter and building materials have very real consequences that connect ontology to axiology. According to Olivetti & Cullen (2018), global annual resource use in 2017 reached nearly 90 billion metric tons, a figure that is expected to potentially more than double by 2050. The sites where the materials are extracted are no longer predominantly situated in Europe and North America, but in Asia, where (again in 2017) 60% of the entire world's material extraction took place. Over the next decade, extraction is expected to rise substantially in Africa, a change that 'helps to improve standards of living in the developing world, but also leads to important environmental concerns'.

This theoretical/practical view of the world as being composed of organic and inorganic matter-energy flows (with a known history and a future that can be anticipated), which fuse and merge into transient materialised or expressed assemblages (such as for instance man-made architectural structures) across space and time, is a fertile starting point if we want to ascertain that more sustainable materials are used in our buildings. It is also, of course, a description of AAAs.

The idea in DeLanda (2016) of an assemblage as a 'concept with knobs that can be set to different values,' a 'parametrised term capable of existing in two different states' able to form ensembles that 'are themselves treated as assemblages, equipped with their own parameters, so that at all times we are dealing with assemblages of assemblages' is well aligned with the AAA design method. The unique history of a building's inception holds the potential to create emergent properties within the design by matching its components in such a way as to make the building possess properties that those components do not have on their own, as well as its own tendencies and capacities. One such capacity (real if rarely exercised) is arguably to *improve* the built environment and *increase its value*, relative to what the world was like before the building existed.

As outlined above, the linear flow of materials that are extracted from nature, transformed into products, used in the built environment, and eventually disposed of, traces the starting point for the strategy, proposed in Schaltegger & Sturm (1990), of *eco efficiency,* an approach 'concerned with creating more value with less impact' that essentially seeks to minimise the amount, speed, and toxicity of the material flows involved. This process, however, can lead to a downgrade in material quality (downcycling) and might also produce rebound effects, as noted in ESCAP (2009), whereby improvements in 'the efficiency of resource-use per unit is outstripped by the absolute increase in demand for the goods and the deterioration of resource efficiency in consumption'.

Opposing such a development, AAA could be used to design *eco-effective assemblages* made of material flows that are transformed to support ecological systems and future economic growth. Rather than minimising the cradle-to-grave flow of materials, Wautelet (2018) suggests that 'the notion of waste [should be] erased' perhaps through the design of what Braungart et al. (2007) call 'cyclical, cradle-to-cradle "metabolisms" that enable materials to maintain their status as resources and accumulate intelligence over time (upcycling)'. McDonough & Braungart (2002) describe the concept of eco-effectiveness as 'working on the right things – on the right products and services and systems – instead of making the wrong things less bad'.

Referencing Waldby (2002) and Thacker (2005), Rekret (2016) explains how progress in different fields, notably 'advancements in computer science that permit the handling of exponentially larger datasets in clinical work,' is driving a development whereby biological materials 'become increasingly available as discrete entities at the level of molecular fragments,' which in turn enables 'the inducement of living processes to increase or change their productivity along specified lines or intensify their self-reproducing and self-maintaining capacities'. This involves, writes Rekret,

> life's construction and engineering at the molecular level of life itself, thus problematising any distinction between the natural and the cultural. However, these conceptual and technological transformations of life have their correlates in material practices involving the separation and abstraction of biological materials from their macro-anatomical sources through mechanisms of dispossession.

AAAs could perhaps 'hack' such mechanisms to produce buildings that generate more energy than they consume: power plants for living in. In 1994, Rolf Disch coined the term PlusEnergy as a designation for such buildings, the first of which was his private residence, the Heliotrope, in Freiburg im Breisgau, Germany. This is a cylindrical building that rotates with the sun, and is described in Disch (2020) as being 'emission-free, CO_2 neutral and 100% regenerative'.

8.6 AAA hegemony

Bearing this in mind, we leave the Aymara model behind and rotate 180 degrees to face the future. To conclude this thesis, we might do worse than to borrow a trick from the deck of Harman (2008). Ending his formidable critique of DeLanda's ontological system, Harman puts the philosopher to a 'hyperbolic test,' imagining that in the year 2030,

> DeLanda's ontology has swept all rivals aside, attaining the status of canonical classic or outright dogma. DeLanda has now replaced analytic philosophy as the very embodiment of the philosophical mainstream – perhaps containing splinter factions (the Harvard and Oxford DeLandians) but not facing much real dissent. Let us take a moment to imagine this scenario, and try to think about the ways in which we would feel liberated and those in which we might feel cramped or stifled.

This exaggeration, claims Harman, 'means the willingness to be falsified, and an openness to surprise'. While these are still very early days indeed, AAA aims to be taken seriously as a solid contribution to present-day architecture and engineering, in theory as well as in practice. It wants the world – or at least the AEC industry – to change in ways that make it impossible for ADs to show up to a client meeting without having designed 100,000 new buildings since the last one. It wants to disrupt a culture that remains *very* silent about its massive contribution to climate change, by creating a new market and a new value network that eventually displaces the established players, pushing today's market-leading (heedless and selfish) firms, products, and alliances into oblivion.

What would happen if AAA were to attain this goal, if, in 2030 to stick with Harman's example, the AAA method – including a new AAA science – had become the gold standard by which the rest of the industry (and its associated academic institutions) measured its success and made its money? Where are the empty rooms to be found in the theory presented here? How would our current thinking need to change, and what would still be missing from the system of ideas and methods?

Despite Herbert Simon's misgivings in Simon (1996) about the 'difficulty of disentangling prescription from description,' it is not very hard to imagine AAA being turned into a new and rigorous scientific branch of its own – much like chaos theory and the study of complex adaptive systems before it – constructed at the intersection of materials science and systems theory, a branch that would study the intricate interactions between material geometries and their contexts, mediated by values derived from dynamic and evolutionary processes. Architecture and engineering are of course two fields that could use the knowledge produced by such a science, but many other disciplines might also benefit from this kind of pursuit, including for instance chemistry, biology, sociology, economics, ecology, and celestial mechanics.

In an attempt to pre-empt the expected (if unfounded) objection that it is 'unscientific' to study a man-made system producing digital objects (such as AAAs), as opposed to factors of the universe such as objects and phenomena found in nature, we could point to non-empirical *a priori* fields such as mathematics and logic, to various fields within the social sciences, or to more recent scientific investigations of manufactured artefacts, including not just individual constructs – CAS, Conway's Game of Life, cellular automata, L-systems, and so on – but also the whole of computer science, robotics, and artificial intelligence. Or we could propose that *all* of science is mediated in ways that at a fundamental level mirror the 'filter' (between the AD and the world) constituted by the AAA, as architect Yona Friedman hinted at when interviewed by Hans-Ulrich Obrist (2002):

> Scientific theories are only supported by what we perceive, by that part of our perceptions that we interpret as the external world. First we make an image of the world, then we try to adapt it to reality (an imaginary one, it should be noted). […] We direct our attention to certain things and not to others: 'we invent a world' (of science), and then we try to adapt to this invention, to prove that it stands up. But our proofs, all our proofs, are solely based on 'statistics' (and statistics doesn't prove anything, it only analyzes the 'frequency' of events, and not the events themselves). I try to see the world not simply as an entity uniquely describable with statistical methods, but as a world composed of individual entities that I (in my theory) call 'granules of space,' entities whose behavior is entirely unpredictable. Of course we may describe their behavior statistically, but we can not predict them from one moment to the next. These 'granules of space' (and their behavior) are unpredictable, erratic.

Friedman's granules of space sound a lot like individuals within the populations of spaces produced by AAAs (whose behaviours can be statistically described), just as his notion that the world of science is basically *invented* can be brought to bear as a counter argument against the view that AAAs are not worthy of study. If we adopt the PET framework, they may in fact constitute *ideal* study objects, due to their digital reproducibility and falsifiability.

Having said that, *material* geometries existing in a *context* is of course something entirely different from the pristine theoretical constructs that populate the study of space in mathematics: the dimensionless points, lines of negligible width and depth, and infinitely extending planes we know from geometry, crisply outlined against a neutral white background that asserts no influence on them. According to Boyer & Merzbach (1991), exceptional mathematician David Hilbert once remarked that in geometry, 'One must at all times be able to replace, "points, lines, planes" by "tables, chairs, beer mugs".' Our imaginary new AAA science could expand on this idea, endowing geometries not only with certain material properties and a physical context, but with attributes such as memory (or systemic feedback based on simulations of future events), the capacity to adapt according to values, and a high sensitivity to initial conditions.

This idea of a future AAA *materialist* science can be further illuminated by considering what Deleuze (1992), in an analysis of Foucault's idea of an 'apparatus' *(dispositif),* calls 'curves of visibility' and 'curves of utterance'. 'Visibility, ' writes Deleuze,

> does not refer to a general light that would illuminate preexisting objects; it is made up of lines of light that form variable figures inseparable from an apparatus. Each apparatus has its regimen of light, the way it falls, softens and spreads, distributing the visible and the invisible, generating or eliminating an object, which cannot exist without it. This is not only true of painting but of architecture as well: the 'prison apparatus' as an optical machine for seeing without being seen. If there is a historicity of apparatuses, it is the historicity of regimes of light but also of regimes of utterances. Utterances in turn refer to the lines of enunciation where the differential positions of the elements of an utterance are distributed. And the curves themselves are utterances because enunciations are curves that distribute variables and a science at a given moment. […] In each apparatus, the lines cross thresholds that make them either aesthetic, scientific, political, etc.

If we allow ourselves to extrapolate from this, we can view each new individual AAA under study to have its own 'regimen of light' – it illuminates/investigates a particular virtual possibility (one singular path through the maze discussed in sections 2.5 and 2.6 above). From aggregates of such studies, regularities, sequences, and patterns can be deduced that operate at the 'higher' level of the form seed, or the even higher level of AAAs in general. Utterances, similarly, are uniquely tied to an individual AAA (in that we explicitly know the input and output data for each design iteration), but can be aggregated into more general enunciations about different combinations of parameter settings and their effects. Studying AAA from different frames of reference (having them 'cross thresholds') can widen the scope further, changing what they shine a light *on,* what they make utterances *about,* paving the way for aesthetic AAA studies, political AAA studies, and so on.

Future AAA studies, then, could focus (following Simon) on the *description of prescription,* the diligent study of how this particular type of complex and constructed artificial assemblage is constituted and functions, how it asserts influence on and is influenced by its context, its environment, other assemblages. They could focus on individual AAA mechanisms – from the anticipation and adaptation that arise when AAAs are connected to weather simulations, as explored in Paper II and Paper V, through to practical issues of mitigating the curse of dimensionality investigated in Paper IV and Paper V – or study phenomena that emerge from a collection of interacting AAAs. They could follow the lead of Paper IV and venture further into material space shifts, charting the relative benefits of particular material systems given a set of predefined objectives and a virtual search space of design solutions. They could enquire into how the performance of actually-built anticipatory adaptive assemblages, such as the Sliding Sidewinders building described in Paper V, (the construction of which is set to commence in 2021) correspond to their virtual precursors.

Alternatively, they could examine the structure of the space of possible rules created by various combinations of objectives and constraints that control material geometries, focusing entirely on how value-based *limits* may be used to calibrate AAAs. 'The concept of limits,' notes Tschumi (1996) ‘is directly related to the very definition of architecture’. Developing a discourse on the agency of architectural constraints is arguably paramount to leveraging the discipline’s methodological potential and epistemological promise, counteracting the tendency highlighted by Tschumi: ‘the narrowing of architecture as a form of knowledge into architecture as mere knowledge of form’. Developing an understanding of the limits controlling AAAs would be one way of producing knowledge by way of architecture.

AAA theory supplies the framework for such studies and many more, explorations that allow many different values, be they gender studies or the chemistry of wood preservatives, to be studied as component parts of AAAs. Still with our backs firmly Aymara-pressed against the future, we may note the similarity between an idealised version of a AAA and a prototypical combinatorial puzzle from the past: the Rubik’s cube (Figure 16), the history of which is outlined in Rubik et al. (1987). Hungarian sculptor and professor of architecture Ernő Rubik’s 1974 invention combines a large state space with a single goal state, highly unlikely to be accessed using sequences of randomly generated moves. (The original advertising famously noted there were ‘over 3,000,000,000 (three billion) combinations but only one solution,’ though the actual number of combinations can be significantly higher than that.) Some strategy combining anticipation and adaptation is crucial to reach the goal state, and each successive move produces a new virtual iteration of the cube’s internal organisation, together with associated data (a record of the number of correctly solved tiles). A number of solutions – known to ‘speedcubers’ as ‘algorithms’ – exist that allow solving the cube in well under 100 moves.

Figure 16: An idealised version of a AAA is similar to the prototypical combinatorial Rubik’s cube puzzle, invented by Ernő Rubik’s in 1974, in that it combines a large state space with a single goal state, highly unlikely to be accessed using sequences of randomly generated moves.

What similar methods might be developed that 'solve' the considerably more complex challenges posed by AAAs, which, to begin with, usually comprise decidedly more than three billion virtual permutations and aims at a Pareto front of equally performing candidate solutions rather than a single goal state? That would be one of the many challenges awaiting future generations of AAA researchers.

Some of the immediate gains under the imagined AAA hegemony outlined above would be obvious. As noted above, the built environment is a large-scale *material* assemblage responsible for between 35% and 40% of both global final energy use and worldwide energy-related CO_2 emissions, with the construction sector using up around 40% of all natural resources extracted in industrialised countries, while consuming almost 70% of electricity and 12% of potable water – and counting. That disastrous trend needs to be reversed by *material* means. If AAA were to become widely adopted, these concerns would almost by definition be addressed in each and every new design project. Logically, in a AAA world, no buildings would ever get built that did not consume less energy than they produced. Every new building would improve the built environment and increase its value, relative to what the world was like before that building existed. All new buildings would be power plants.

The AAA ontology would provide a solid grounding for theoretical extrapolations. The AAA methodology would irreversibly alter the role of ADs, giving them more power and an increased potential to make a real difference. The AAA epistemology would provide unprecedented ways of learning from practice and put into practice that which has been learnt. The AAA axiology would provide opportunities to develop new and exciting ways to connect evolutionary architecture to ethic and aesthetic concerns, endowing the assemblages described by Deleuze and DeLanda not just with knobs that control values, but with value-based knobs. Furthermore, in ontological terms, AAA improves on DeLanda's assemblages in one crucial aspect: they are not just defined in terms of *capacities*, but always come with well-defined, explicit *properties*.

The AD role of being a creator of species of spaces developed in Paper I would no longer be new, but simply an accurate description of what ADs do: create a more sustainable built environment by predicting, exploring, evaluating, and accelerating an abundance of possible future design trajectories through the use of AAA as a generative and evolutionary computational technique. The additional complexity – in terms of design process, formal intricacy, and material performance – associated with the strategies developed in Paper II to leverage site-specific constraining flows of data that allow AAAs to be parametrically influenced by past or future events and unique project conditions would be standard procedure. The 'artificial separation between architecture, engineering, and material design' attacked in Paper III would be challenged, and we would be closer to achieving that article's vision of a 'contextual materials engineering technology'. Much-developed incarnations of MPT diagrams would be used to analyse the performance of potential material systems given multi-dimensional sets of auxiliary loads combined with contextual data updating in real time, as foreshadowed by Paper IV. The case study put forward in Paper V would be viewed with nostalgia as the first qualitative study of a AAA design process, and studied by an international body of architecture students as a preparatory exercise before their excursions to the Sliding Sidewinders outside Stockholm – the world's first AA building.

CONCLUSIONS & FUTURE STUDIES

9. CONCLUSIONS & FUTURE STUDIES

This chapter summarises the progress made in the previous chapters, offers a response to the overarching question of the thesis, discusses scientific contributions and relevance to the industry, before suggesting possible future studies.

Perhaps needless to say, the present thesis presents a collection of tentative beginnings within a field of study that opens up almost infinite opportunities for further research. Its various shortcomings will undoubtedly become manifest as research proceeds, but the longest journey begins with a single step. The aim was to investigate and develop a framework for the transformation of material knowledge – properties and capacities at various scales – into generative mechanisms that can be used to optimise an architectural design for different loads and situations it may be subjected to during its life cycle, and have it adapt to its context.

This led to the development of the anticipatory adaptive assemblages (AAA) concept, position and examine it within the four philosophical branches of ontology, methodology, epistemology, and axiology, and discuss how it might be further developed through future studies. Following this exercise, we have arrived at the following conclusion: the AAA framework provides a promising theoretical and pragmatic opportunity to leverage the power of evolutionary computing as a means to increase the architectural performance of our built environment, in an era marked by the insight that just aiming for sustainability is no longer sustainable, a time that cries out for ways to optimise the fragile spaces we construct to secure the survival of our species.

The Background chapter situated the framework within its scientific context. The Ontology chapter showed how the theories at the heart of AAA, derived from Deleuze and Delanda, can be connected to and support an assemblage-based realist ontology. The Methodology chapter introduced pragmatic methods for using AAA in practice, including a step-by-step example that illustrated the successive production of a simple anticipatory adaptive assemblage. In the chapter on Epistemology, AAAs were turned into parametric epistemic things (PETs), a novel framework for digital (and possibly automated) experimentation. The Axiology chapter offered a critical examination of the axiological mechanisms that can be used to sculpt values into AAAs. The objective was to discuss how AAA ties in with truly deep questions about why, how, and at what cost we should go about designing our built environments. This led to the concluding Discussion, which also discussed links to big data and plus-energy buildings, introduced the concepts of presilience and postponism, and put AAA to a hyperbolic test.

The overarching question of the thesis has been this: what might be a valid framework for the use of building materials data when it comes to optimising the design of architecture and engineering projects? Whether or not AAA is the answer to that question, its author hopes to have demonstrated that the different entities that make up the architecture, engineering, and construction (AEC) industry have an individual and collective responsibility to consider alternative strategies for how to lower the between 35% and 40% of global final energy use and worldwide energy-related CO_2 emissions that it is responsible for. Furthermore, he hopes to have demonstrated that allowing our knowledge of material characteristics to directly influence geometries (assemblages) that can be optimised (adapted) by simulating (anticipating) their future effects on the world's social, economic, cultural, and environmental sustainability is one promising way forward.

Scientific contribution

This thesis adds scientific value in at least five areas:

1) By introducing the theoretical and practical research agenda proposed as the study of AAAs. This not only fills a gap in the existing literature, but could also, similar to John Holland's invention of complex adaptive systems (CAS), encourage a wide range of future studies in various fields. Several of the individual processes described and used – such as the translation of the principle of phase diagrams into material phase transition diagrams (MPTs), the proposal to endow existing life cycle assessment (LCA) practices with generative capabilities, and the organisation of constraining parameters and evaluation mechanisms into new taxonomies – contribute to the state of the art while inviting scientific responses.

2) By constructing a series of tools, including the Grasshopper definitions shared in the public domain, and at times exemplified as parametric epistemic things (another contribution). These instruments can be used to construct MPT diagrams, create parametric pinwheel tessellations of the plane, compare in a generative fashion LCA values for a set of different wall compositions, and so on, all of which could support future studies.

3) By inventing a series of new concepts – including auxiliary load, material phase transition (MPT), generative life cycle assessment (GLCA), parametric epistemic thing (PET), presilience, and postponism – that invite further experimentation and prompt new interpretations of the existing literature.

4) By obtaining results as part of the individual experiments, which could have an impact on new scientific studies, and become the starting point for additional research projects and papers that might promote further reproduction through corresponding citations.

5) Over and above the experiments it describes and the results it reports, Paper V fills a particular gap by the simple fact that it evaluates an actual implementation of meta-heuristic design processes in architecture (as opposed to the more prevalent theoretical exemplifications); such field studies are curiously underrepresented in the literature.

Relevance to the industry

In 2020, very few buildings in industrialised countries are designed by an unaccompanied architectural designer (AD). Most work is carried out in extended design teams that include additional competences: architects, civil and structural engineers, clients, surveyors, builders, financial controllers, sustainability consultants, real estate agents, advertising agencies, material suppliers, and so on, that together – as an assemblage – create the building. The primary potential benefit to industry presented by AAA is the way it establishes the scaffolding needed to construct unifying processes and common protocols for such design team assemblages to work together in quantifiable ways toward shared goals.

The pragmatically-oriented Paper I presents two strategies that could be adopted by the industry: 1) the use of timber as a primary retrofitting material, and 2) an energy-producing, mass-customised, scalable building typology made from wood. But it also provides some applicable theoretical insights, including the idea that optimisation is not so much about 'problem solving' as 'answers searching,' the credo that form follows fitness, and the crucial difference between the complex and the complicated. Paper II discusses the design of urban wooden façade systems, including a novel design for a glass-laminated cross-laminated timber (CLT) panel, while pointing to the potential development of design processes in materials science that 'facilitate a translation between new knowledge of material behaviour at the micro scale and actual changes to the design of an architectural geometry at the macro scale'. Paper III develops this idea, identifying a potential gap in the market. The MPT diagrams and auxiliary loads analyses discussed in Paper IV and Paper V could be further developed into stand-alone products and services.

Furthermore, the individual papers make connections to existing approaches in neighbouring fields, and show some ways in which they could be introduced to the AEC industry, as exemplified by the teleodynamic approach presented in Paper II, the 'contextual materials engineering technology' explored in Paper III, and the benchmarking discussed in Paper V.

The value of complexity: future studies

With our backs again firmly pressed against the future, we can study the past – and carefully review the text above – for clues as to what forthcoming studies might move AAA forward. As Holland (2014) reminds us, the original meaning of the word 'complexity' was as an ordinary noun used to describe objects with many interconnected parts. While this definition applies to AAA (and most assemblages, which are consequently complex), someone using the term today is more likely to refer to complex *systems*, in which, writes Waldrop (1992), 'a great many independent agents are interacting with each other in a great many ways':

> Think of the quadrillions of chemically reacting proteins, lipids, and nucleic acids that make up a living cell, or the billions of interconnected neurons that make up the brain, or the millions of mutually interdependent individuals who make up a human society.

Indeed. Or think of the interconnected and mutually interdependent values that make up the transgressive tissue of a AAA. Following Mitchell (1996), we may conclude that all of these complex structures have at least three fundamental characteristics in common: 1) they are self organising and emergent, 2) they are adaptive, 3) they are dynamic in ways that make them complex rather than complicated. Let us briefly examine these qualities from a AAA point of view. As Paper I states:

> There is a tendency within the building industry to fear added complexity when really the concern is (or should be) about wasting time on complicated processes. Many people still get the complex mixed up with the complicated, and use the words interchangeably. A little sugar helps bring the flavours together in a tomato sauce; it balances out the acidity and enhances the natural sweetness of the tomatoes. This is an example of something that is complex without being complicated (in the systems

> theory literature, 'complicated' often refers to something with many parts, whereas 'complex' refers to an unpredictable, emergent behaviour).

This quote touches upon the first and last characteristics. The tomato sauce expresses *emergent* qualities: it is something more than simply the sum of its parts. Those parts may include onion, garlic, olive oil, tomatoes, salt, pepper, and sugar (not to mention carrot, celery, basil, parsley, capers, olives, and a dash of wine; to quote David (1954), there are 'as many ways of making it as there are cooks in Italy'), but the resulting *pomarola* or *marinara* or *puttanesca* is not primarily 'about' the parts, but about the way they go together. Writes Mitchell (1996):

> after three hundred years of dissecting everything into molecules and atoms and nuclei and quarks, (scientists) finally seemed to be turning that process inside out. Instead of looking for the simplest pieces possible, they were starting to look at how those pieces go together into complex wholes.

The same emergence is present in hurricanes, traffic, the stock market, and biological life itself (an emergent property of chemistry). All those entities – and countless more in the universe – have properties that their parts do not have on their own; interdependent and unpredictable properties that *emerge* only when they come together, only when their independent parameters or variables interact in a larger whole, an assemblage.

As it expands, the universe is physically growing increasingly complex, and so is our understanding of it. From the Big Bang theory of Lemaître (1927) to the discovery of phosphine gas in the clouds of Venus reported in Greaves et al. (2020), our different sciences march to the beats of ever more complex drumming. Similar expansive trajectories can be traced in architecture, which has moved from the primitive hut investigated by thinkers such as Laugier (1753) and, in a sense, Heidegger (1951) to the profusion of increasingly complex BIM-controlled geometries making up our contemporary built environment, a leap in design and production assisted by accelerated developments in high-speed computing, advanced software development, and computer graphics.

In AAA, there is a very obvious inherent *value* to this dynamic complexity: the more dimensions we can add to the mathematical optimisation problem that yields the final assemblage, the better our chances of meeting the brief in a satisfactory fashion. This is easy to forget in the present era, in which a common credo in the business self-help literature is the idea that we should 'cut complexity to add value'. Again, this is mistaking the complex for the complicated. If you 'cut complexity,' you don't get *marinara*. You get a tomato.

What about the second characteristic, the adaptive nature of a complex system such as a AAA? As clearly illustrated in Simmons (2010), adaptation is key to survival in nature and to mechanisms of evolution, which implicitly optimises organisms. AAAs are adaptive in at least three ways: they produce assemblages that adapt to new situations, using procedures that adapt to the data provided, in order to support strategies that adapt to explicit goals balanced at the theoretical intersection of architecture and axiology.

As is the case with its biological correlative, the evolutionary logic at the heart of AAA can feasibly make such assemblages a robust response to changing environments: detaching the AAA from one context and plugging it into another is highly likely to produce a change in form as the assemblage *adapts* to its new environment. Likewise, again borrowing from de Saussure (1916), we may consider the evolutionary operations at work *inside* the genetic algorithms that shape the AAAs to be *synchronically* adaptive (making adjustments to solve the present objective function), but also to be *diachronically* adaptive (making adjustments over time to become better at solving particular kinds of objective functions), as noted by Holland (1984):

> Genetics provides us with a canonical example of a complex search through a space of ill-defined possibilities. [...] It is possible to give genetic processes an algorithmic formulation that makes them available as control procedures in a wide variety of situations. By using an appropriate production (rule-based) language, it is even possible to construct sophisticated models of cognition wherein the genetic algorithm, applied to the productions, provides the system with the means of learning from experience.

This was a potentially fertile and interesting area of study when Holland discussed it almost 40 years ago, and it is even more fertile and interesting today, when the technology has finally caught up with his thinking, but many of the difficulties (including computational strain due to high dimensionality) that attend complex ill-defined problems remain.

The AAA theory has obvious ties of kinship to the concept, developed in the mid 1980's at the Santa Fe institute, of complex adaptive systems (CAS), in which, as Miller & Page (2007) explain, a perfect understanding of the individual parts that make up a system does not automatically convey a perfect understanding of that system's behaviour. CAS are well outlined in Holland (1995); background notes on their origin can be found in Dodder & Dare (2000). CAS and AAA both stress the importance of self-organising interaction between heterogeneous parts in an evolutionary and emergent framework, defined in Levin (2002) by three key properties: '(1) diversity and individuality of components; (2) localized interactions among those components, and; (3) an autonomous process that uses the outcomes of those interactions to select a subset of those components for replication or enhancement'. The statement in Holland (1998) that in CAS, 'the whole is more complex than its parts' certainly holds for AAA.

The link to architectural axiology – ethical and aesthetic considerations – makes this even more obvious, as it connects AAA's systemic features of adaptation next to the contemporary adaptation of materials to digital fabrication processes and vice versa, a current development that Borden & Meredith (2011) establish has

> driven a needed expansion of our methods of production and fabrication. Anything can be cut with ease and precision. Materials can be bent, rolled and cast with seemingly infinite flexibility. The design application limits of a particular material are no longer seen as inherent within the material itself, but rather as functions of surrounding processes. Tools and materials have become inseparable and indistinct from one another. There is no material that is unmediated.

Borden and Meredith note that ‘when tree trunks cease to be automatically understood as cylindrical fibrous bundles and can instead be conceived as stacks of veneer sheets laminated without consideration of wood grain, or sawdust molded and pressed together with chemicals to achieve dimensional stability, we find that our nostalgic default material understanding has been fundamentally destabilized’. But more important than this phenomenological comment is the way new fabrication technologies can promote an *adaptive materiality* in architecture: when tools and materials become inseparable, the value-laden question of *why* and *how* we wish to materialise something comes to the fore. This is the rationale at work in experiment C of Paper V, in which a material phase transition study optimises for embodied energy: the (anticipatory) mechanism of predicting the auxiliary loads (first introduced in Paper IV) of a potential assemblage making it adapt its material section to meet predefined objectives of an axiological/architectural nature.

This is one potential area for future AAA studies, as discussed in Paper IV and Paper V: how can MPTs be used as analytic tools for the material specification of buildings. In what ways can AAAs be used to generatively connect our understanding of different materials’ auxiliary loads to the production of architectural form and engineering structures, to push LCA into GLCA? Much work remains to be done on the development of MPT diagrams: how can they be generalised and in what ways can they be improved, in particular by leveraging their inherent digital nature and susceptibility to becoming part of big data-based systems? How can they be made to showcase more dimensions than the three investigated thus far?

Another potential area for future studies already mentioned above is the establishment of protocols for different modes of AAA definitions. The AAA ontology, the initial embryo of which was developed in Paper I, could become the topic of futures investigations, in particular with regards to its unique congruence with and connection to the AAA methodology. These two areas might benefit from being developed simultaneously: the theorising in Paper II about the ways in which teleodynamic operations can give rise to informed architectural geometries is one example of how an external conceptual injection – in this case from the theories put forward in Deacon (2012) – can be used to perturb and provoke AAA, forcing it to question itself, pushing it in new directions. In the particular case of that paper, the theoretical result was primarily to do with the anatomy of the methodological process, but it also went to show how material strategies can be connected to this ontological-methodological framework.

This points to yet another important area for future AAA studies: its potential to inform decisions pertaining to axiological-material aspects of architecture and engineering. Engineers, for instance, are typically good at optimising structures for weight and efficiency, but not as good at taking into account less obvious aspects of the material fabric: its global warming potential, its haptic qualities, its psychological values within. Ikei et al. (2016), for instance, reviewed scientific studies of the effects of wood-derived stimulations on olfactory, visual, auditory, and tactile sensations using physiological indices such as brain activity and autonomic nervous activity), and so on. How can such aspects be made not just generative but effective as control measures within the AAA design process?

While so far we have considered only the positive potential of AAAs, it should be duly noted that anticipatory adaptive assemblages are of course also associated with negative risks, including but by no means limited to what Hui (2015) refers to as the possibility for 'algorithmic catastrophes,' cataclysms that arise from 'the failure of reason' in automated processes (as an example, Hui mentions the algorithmic trading-induced 'flash crashes' that have paralysed entire financial markets in seconds). As Wiener (1966) noted already half a century ago, the 'penalties for errors of foresight, great as they are now, will be enormously increased as automatization comes into its full use'. Even before then, in Wiener (1960), the famed cybernetician warned that

> if we adhere simply to the creed of the scientist, that an incomplete knowledge of the world and of ourselves is better than no knowledge, we can still by no means always justify the naive assumption that the faster we rush ahead to employ the new powers for action which are opened up to us, the better it will be.

This seems to be what Hui (2015) has in mind when noting that the automation of machines

> will be much faster than human intelligence, and hence will lead to a temporal gap in terms of operation. The gap can produce disastrous effects since the human is always too late, and machines won't stop on their own.

Indeed they will not, and inventing strategies for mitigating such risks would be another important area of future AAA studies. But this situation also points to a weakness in the Aymara model of turning our backs to the future: the machines won't stop while we evaluate the knowable past. Only through acts of anticipation, only by projecting into the uncertain future can we begin to close the gap between highly intelligent AAA designs and the limited intelligence of the human mind that produces them.

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FURTHER READING

11. FURTHER READING

The enquiring reader may consult the following ten books (including a visionary and inspiring PhD thesis), arranged in chronological order by year of publication, for additional and more detailed coverage of various aspects of some elements that the present thesis samples and synthesises into AAA theory. While not on this list, Steadman (1979), Simon (1996), Rheinberger (1997), Rutten (2011), and Kleinherenbrink (2019) were runners up.

John Holland (1975)
Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence
Holland's classic initiated the study of adaptation in artificial systems by way of genetic algorithms, presenting theoretical foundations and exploring applications that include the author's invention of complex adaptive systems.

Gilles Deleuze & Félix Guattari (1980)
A Thousand Plateaus: Capitalism and Schizophrenia
The book that introduced the 'assemblage' *(agencement)* concept. This second and final volume of Deleuze & Guattari's collaborative *Capitalism and Schizophrenia* project is a provocative joyride through a conceptual landscape bursting with pop, maths, and science.

Robert Rosen (1985)
Anticipatory Systems: Philosophical, Mathematical and Methodological Foundations
How do biological systems anticipate their environment? Theoretical biologist Robert Rosen attempts to answer that question in this outstanding contribution to a field scholars such as Alfred North Whitehead, Buckminster Fuller, and Richard Feynman were interested in.

Ernest Mayr (1988)
Toward a New Philosophy of Biology: Observations of an Evolutionist
28 essays on everything from adaptation to macroevolution, collected in a book that Mayr, in his foreword, describes as an attempt 'to strengthen the bridge between biology and philosophy, and point to the new direction in which a new philosophy of biology will move'.

Melanie Mitchell (1996)
An Introduction to Genetic Algorithms
Brief and accessible, Mitchell's remarkably clear book on genetic algorithms is as readable as her initiated 'guided tour' of complexity. Having worked with both John Holland and Douglas Hofstadter, this author's sharp insights and dry wit makes for the perfect introduction.

Stuart Kauffman (2000)
Investigations
Physical systems (for instance AAAs in a biosphere) affect their dynamic environments and are in turn affected by them. Kaufmann views such systems as autonomous agents, and uses them to investigate, with breathtaking beauty, that oldest of questions: what is life?

Luisa Caldas (2001)

An Evolution-Based Generative Design System: Using Adaptation to Shape Architectural Form

Despite her persuasive arguing, the processes Caldas presciently proposes in this remarkably early and prophetic doctoral thesis have still not become compulsory methods or even inescapable activities in common architectural and engineering practice. A formidable study.

Manuel DeLanda (2006)

A New Philosophy of Society. Assemblage Theory and Social Complexity

Marking the real beginning of DeLanda's assemblage theory, this is a AAA cornerstone. An ontological study of social complexity, DeLanda's anti-essentialist 'reconstruction' of Deleuze examines how relations of exteriority between autonomous components yield emergence.

Terrence Deacon (2012)

Incomplete Nature: How Mind Emerged from Matter

Used as a creative vehicle in Paper II, neuroanthropologist Deacon's controversial study of 'aboutness' – concepts such as intentionality, purpose, and function, which the author labels as 'ententional' phenomena – challenges preconceived notions of causation and constraints.

Manuel DeLanda (2016)

Assemblage Theory

Featuring two books by DeLanda in a list of ten goes some way towards showing the influence this author asserts on AAA theory and this thesis. The culmination of 25 years of speculations on assemblages, this is a transformative overview of the philosopher's findings.