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A search for performative logics of materials, reflecting on self-imposed constraints and how evolutionary solvers can be used for material-based architectural optimisation of structures.

Conflict and compromise in multi-storey timber architecture

Magnus Larsson, Alex Kaiser, Ulf Arne Girhammar

Form follows fitness

In January 1995, architect John Frazer's groundbreaking study *An Evolutionary Architecture* was published to coincide with an exhibition of the same name at the Architectural Association in London.[1]

The book proposed a new methodology for architectural design based on a radical repositioning of the role of the architect. Its fundamental premise: that an abundance of possible future design trajectories could be predicted, explored, evaluated, and accelerated through generative and evolutionary computing techniques. These could be directed towards a more sustainable built environment designed using form-generating processes that employ the scripting of code as a representation of genetic characteristics, allowing architectural structures to be treated as a form of artificial life.

Frazer argues that as design iterations, such as study models or sketches, begin to operate like organisms, developmental and evolutionary processes can be made to act upon the resulting assemblies in response to their specific sites and contexts, which come with (for instance) unique environmental and weather data, programmatic concerns, and functional performance criteria. As Gordon Pask writes in his 'Foreword', Frazer's ideas suggest a far-reaching change in practice: '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.'

Frazer was ahead of his time. In 2010, David Rutten, a talented software developer with Robert McNeel & Associates, released Galapagos, an evolutionary solver that works with Rutten's own Grasshopper graphical algorithm editor, which has been pivotal to the recent transformation of parametric design practices. Arguably, Galapagos brought evolutionary solvers to the masses interested in digital design. The plug-in made it relatively simple to create a wide spectrum of design iterations based on evolutionary logic.[2]

The towers of architecture's Steel Age are currently giving way to those of the new Timber Age – a more appropriate material era that is emerging slowly as the natural successor to its energy-intensive precursor. The time has come to update architect Louis Sullivan's 1896 proclamation that 'form follows function' for an age in which his tall steel skyscraper appears to be evolving into the tall timber



1 Beyond Endurance (perspective render). Energy production vs quality of life.

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2 Against the Grain (perspective render). Many opposing conflicts – 'versuses' – yield compromises within the fitness landscape.

skyscraper. This rare opportunity to update a building typology should be informed by a better precept: that form follows compromise.[3]

As opposed to the black-and-white world of Ayn Rand's famously stubborn architect protagonist, Howard Roark,[4] 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.

One way to use the compromise as a constructive tool is to investigate the concept of 'fitness' through evolutionary computation. If we allow several competing objectives, or genes, to participate in the creation of successful compromised positions (genomes), we might find interesting and novel material and spatial organisations between the controlled and the serendipitous. 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? *[1]*.

Another way of saying that form follows compromise is to announce that form follows fitness. But fitness, in biological evolution, is a tricky concept: it is often difficult to explain exactly what it means to be fit (though it is usually not to do with being the strongest, bravest, fastest or most vicious). As David Rutten has argued, 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*.[5]

The notion of fitness as a driver of form introduces an element of competition to the design process: evolution is based on variations in form that allow some individuals to succeed while others fail. Some might simply survive, others will flourish in their environments, all depending on underlying (and typically invisible) rules of competition. In simplified biological terms, fitness describes how well a particular genotype leaves offspring in the next generation, relative to the competition from other genotypes. If the colour of their furs helps white bears to consistently leave more offspring than brown bears, then white bears have a higher fitness than their brown counterparts *[2]*.[6]

Fitness is relative across space and time. Contextual circumstances, such as a genotype's living environment, will have an impact on its fitness and the fittest genotype during an ice age will probably not be the fittest after that ice age. Despite this absence of absolute standards, fitness remains a convenient theory because it includes everything that matters to natural selection – from survival via mate-finding to reproduction – within one idea or system, summarised by evolutionary biologist Richard Dawkins as a collection of 'robot vehicles blindly programmed to preserve the selfish molecules known as genes'.[7] The fitness of such a survival machine, or genotype, is not only defined

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by its ability to survive but by a wide range of capabilities that ultimately secure the transmission of its genes to the following generation. The relative aptness of differing genotypes in this regard is key to the evolutionary theory.

For architecture, such a framework suggests that form should become a response to competition – an ideal, yet subjective, equilibrium between conflicting, controllable objectives. The role of the architectural designer becomes that of building digital architectural 'robot vehicles' by first inventing a strategy, then setting up and manipulating the rules of competition and finally deciding – or formulating rules to decide – which structures are the most promising compromises. In this context, the creative genius of the architect is defined through methodical acts of continual development, refinement, and optimisation.

Furthermore, this methodology allows for important decisions to be deferred, and alternative options evaluated, until the last responsible moment – a potentially crucial side effect that opens up new possibilities for further research to be conducted, designs to be perfected, time-critical processes to be refined, and money to be saved.[8] The architect, of course, remains in charge of such a process. As strategist and creator, (s)he brings a set of preferences to the proceedings that arguably direct their trajectories. To quote Nobel Prize-winning American political scientist, economist, sociologist, and psychologist Herbert Simon, such a decision-making theory [9] must include 'not only the reasoning processes but also the processes that generate the [designer's] subjective representation of the decision problem, his or her frame'.[10]

All structures are, arguably, reactions to implicit or explicit forces that act upon them. As Nader Tehrani has pointed out, such forces might define a constructive problem of statics, or a challenge for the construction of meaning.[11] Whatever objectives we choose to optimise for, our starting point should be how to strategically define and control these forces. While not as catchy and nicely alliterated, based upon the design methodology outlined here, a better credo for our current Timber Age might then be: 'Form follows compromise follows fitness follows competition follows structure follows forces follows strategy.' The present investigation aims to envisage how interesting architectural structures might be achieved through the implementation of such a novel evolutionary framework, with a particular emphasis on the design of multi-storey timber buildings.[12]

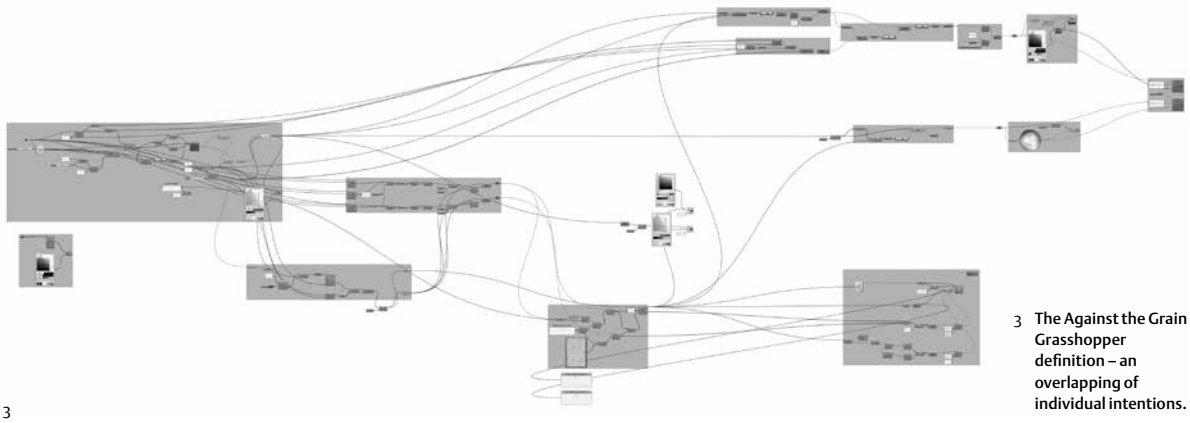
At its core, this idea for how to conceive architectural structures is about a process that could begin with deciding on what might be of essence and perhaps end with constructing and deploying processes that help decide which of those aspects are more crucial than others. The last word is always with the designer, as a set of rules is not worth much without accompanying guiding principles. To quote eighteenth-century Scottish philosopher Thomas Reid, the laws of nature are 'the rules according to which the effects are produced; but there must be a cause which operates according to these rules. The laws of navigation never navigated a ship. The rules of architecture never built a house.'[13] Allow the principles of architects equipped with the logics and pragmatic software power of evolutionary solvers to guide those rules, however – and they will.

Answers searching: comparing the incomparable

Architecture has the distinctive ability to synthesise a multitude of haptic inputs into a coherent whole. Architect Steven Holl points out that 'only architecture can simultaneously awaken all the senses – all the complexities of perception'.[14] He argues that, in the modern city,

> [...] *phenomenal and experiential complexities develop only partially by intent. More frequently, they result accidentally from the semi-ordered, yet unpredictable, overlapping of individual intentions*.[15]

The production of such an 'overlapping of individual intentions' *[3]* is presented here: a range of competing motives – motivating forces – bring out the motif – theme – of the architecture through a 'duality of intention and phenomena'.[16] Architecture, when viewed in this way, becomes a quest for motives through motifs, a question of perception. It deals with the qualities carried by, and experiences made possible through, our capacity to perceive the complexities of the built environment. The question appears again to be one of conflict and compromise in architecture: an attempt to combine the paradoxical; amalgamate



3 The Against the Grain Grasshopper definition – an overlapping of individual intentions.

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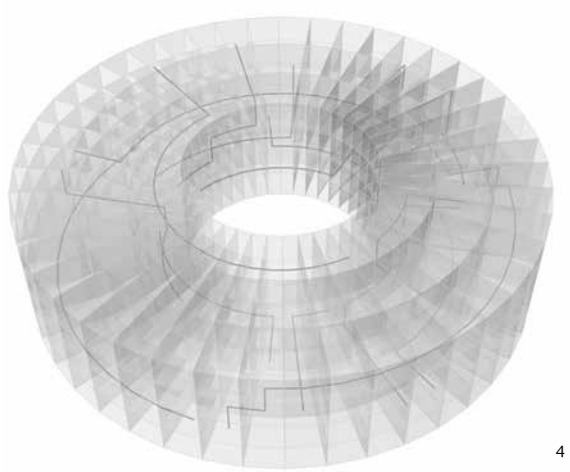
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the seemingly incommensurable; synthesise contrasting elements, divergent data or dissimilar systems into a coherent whole. In short, we seem to be looking for a way to combine apples and oranges into something new.

The famous idiom about comparing apples and oranges refers to the apparent differences between items that are popularly thought to be incomparable, like apples and oranges. It may also indicate that a false analogy has been made between two items, such as where an apple is faulted for not being a good orange. This notion of incommensurability is clearly inadequate in the context of multi-objective optimisation strategies like the ones discussed here, which focus on multiple-criteria decision-making in situations where more than one objective function is to be optimised simultaneously. Armed with such strategies and methods, the key question becomes less about whether something is comparable – and therefore, in a design context, combinable – with something else (it clearly is) than about the measure of what is considered a desirable outcome in a given situation. That is, to stick with the analogy, how much apple and how much orange goes into, say, the blended fruit juice we are designing.[17]

The identification of those characteristics that contribute most to the overall value of the design is crucial and, typically, the criteria (or objectives) involved are competing with each other: thermal comfort vs material cost, insulation properties vs daylight values, attention to detail vs time of construction, structural integrity vs sustainable transportation measures, and so on. Achieving the optimal value for one of those conflicting objectives requires a compromise to be made with regard to one or more of the other objectives. In practice, this compromise is usually based on the search for what might be called an asymptotically optimal solution. Asymptotic because, with the added complexity of multiple objectives positioned within a vast 'fitness landscape', the resulting compromises will rarely be fully optimal, only aspire to follow a trajectory towards such a state[18] *in accordance with the designer's subjective preferences*. To quote Simon again: 'Since my world picture approximates reality only crudely, I cannot aspire to optimise anything; at most, I can aim at satisficing. Searching for the best can only dissipate scarce cognitive resources; the best is the enemy of the good.'[19]

The subjective act of designing is not so much a matter of resolving problems as one of evaluating possible experiences based on a strategic definition of variables and limiting factors. Optimisation is not so much about 'problem solving' as 'answers searching'. Design through optimisation becomes the process of searching for the maxima or minima of our objective functions while satisfying all the required design constraints. So long as we can quantify the objective functions – preferably through a system that allows us to assign them individual importances or 'weights' – contemporary computer technologies allow us to analyse alternative designs with unsurpassed speed and accuracy in order to search rationally through a range of potential solutions to find the optimal compromise *[4]*.



4 Objective functions are assigned individual weights to allow for 'answer searching' at the heart of the evolutionary design process.

In evolutionary biology, organisms that produce more surviving offspring are more fit, while those that produce fewer are less fit. Differences in fitness may be due to differences in survivorship, fecundity, or both. Any 'allele', one of a number of alternative forms of the same gene or genetic locus, that affects either or both of these will be subject to natural selection. There are also alleles that decrease survivorship but increase fecundity and *vice versa*. It follows that being fit can be viewed as a relative position that changes with context and that it is quite possible for the same property or characteristic to go from being fit to becoming unfit over time as the underlying situation changes. A baby elephant on its own is quite vulnerable while a grown-up elephant in a herd has few natural enemies.

Sewall Green Wright was a US geneticist known for his influential work on evolutionary theory. In 1932, he introduced the idea of studying evolution by visualising the distribution of fitness values as a kind of landscape, in order to better understand the relationship between genotypes and reproductive success. The model Wright proposed allows the relationship between genotype or phenotype and fitness to be modelled as an evolutionary surface or fitness landscape. Mean population fitness is the 'height' of the landscape (plotted on the 'z' axis) against horizontal ('x' and 'y') axes representing continuous phenotypic traits. The height at each point represents the corresponding organism's fitness. Natural selection leads to a population climbing the nearest peak, while genetic drift causes random wandering. The combination of all possible genotypes, their degree of similarity, and their related fitness values becomes the fitness landscape, upon which the population can follow various mutational paths through its evolution.[20] Fitness landscapes offer helpful visualisations of our field of potential compromises. It doesn't give us a final

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design solution but rather a series of iterative suggestions that move towards the best possible compromises given the circumstances. We can then use algorithms (that is, solve equations) to bring us closer to an optimal 'final' situation – the best, or least bad, compromise between given objectives *at the time of turning off the optimisation process.*

While evolutionary solvers are used to optimise for certain qualities, the solver itself knows nothing about what an optimal solution to the situation in question might be. Genetic or evolutionary algorithms can at best find a good solution to a reasonably well-scaled model.[21] As the evolutionary method doesn't rely on derivative or gradient information, the solver has no way of determining whether a given solution is optimal. It can only tell whether it is 'better' than the solutions it has found previously. The solver never knows when to stop searching for solutions. Left to its own devices, it will simply keep feeding back new suggestions through a near-endless stream of potential vectors and locations within its search space of possibilities.

Evolutionary solvers

The mechanism of search has always been an important conceptual tool for computational problem solving. Alan Turing proposed various kinds of search as building blocks toward his vision of machine intelligence:

> *Further research into intelligence of machinery will probably be very greatly concerned with searches* [...] *There is the genetical or evolutionary search by which a combination of genes is looked for, the criterion being the survival value. The remarkable success of this search confirms to some extent the idea that intellectual activity consists mainly of various kinds of search.*[22]

Heuristic search in particular – for which a computer seeks the answer to a problem by searching through the space of all possible candidate solutions in search of promising areas – has played an important role in artificial intelligence.[23] However, heuristics only take us so far. Since the approach is based on specific knowledge of the target problem, a universal search algorithm that is good for all problems does not exist. An algorithm that performs well in one class of problems is guaranteed to perform poorly in another. We need algorithms aimed at a particular problem or problem class. With enough domain knowledge about the problem, a good deterministic algorithm will suffice. But if the domain knowledge is incomplete – too complex, too vast, or both – the best we can do might be a random or brute-force exhaustive search. However, these problems share a key property that we can use to guide this search: small changes in the form of a solution cause small changes in the resulting quality of the solution. Stochastic search algorithms are based on this key property. Many stochastic search algorithms exist, including simulated annealing, stochastic hill-climbing, tabu search, ant colony optimisation and evolutionary computation.[24]

While the origins of evolutionary computation can be traced back to the late 1950s, evolutionary programming as we know it was devised by Lawrence J. Fogel in 1960 while serving under Richard Bolt at the National Science Foundation in America.[25] At the time, the field of artificial intelligence was focused on two strands of research: modelling the human brain (neural networks) and modelling the problem solving behaviour of human experts (heuristic programming).[26] Realising the inherent limitations of those methods – that they 'model humans rather than the essential process that produces creatures of increasing intellect: evolution'[27] – Fogel focused on how simulating evolution could bring about intelligent behaviour, defined as being able to predict one's environment and respond suitably in light of a given goal.[28] Rather than modelling the end product of evolution, the idea was to model the process itself as a vehicle for producing intelligent behaviour.[29] Arguably, this strategy for achieving intelligent behaviour in machines for thinking, computers, could also be used to produce intelligent behaviour in 'machines for living' – buildings.[30]

In spite of these early origins, the field of evolutionary computation remained relatively unknown to the broader scientific community for almost three decades.[31] This was partly to do with computational power: Fogel's original experiments were conducted on an IBM 704 which had a running speed of about half that of an Apple II or Commodore 64.[32] In fact, the primary efforts in evolutionary programming were decades ahead of the computer equipment needed to use them.[33] Despite Fogel's 1964 paper drawn from his PhD 'On the Organization of Intellect',[34] and work produced in the early 1970s by Ingo Rechenberg and John Henry Holland, it wasn't until Richard Dawkins's 1986 book *The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe without Design*[35] that evolutionary computation was definitively brought into the spotlight.[36]

Evolutionary computation strategies essentially search for:

> [...] *good solutions to problems by testing large number*[s] *of candidate solutions, selecting the 'better' ones and randomly changing them to form a new set of candidates to be tested. This process repeats until a 'good enough' solution is found or until the computational resources are exhausted.*[37]

The algorithms mimic the process of natural evolution, 'the result of the interplay between the creation of new genetic information and its evaluation and selection'.[38] This neo-Darwinian model of organic evolution is based on the process of single individuals of the population at hand being affected both by its peers – food competition, predators, mating – and its environment – food supply, climatic challenges, and so on. An individual that performs well under the given conditions has a better chance of reproducing, with the offspring inheriting its parental genetic information, leading to a permanent production of novel genetic information and differing offspring.[39] Rather than attempting to model the overt mechanisms of genetics as found in nature, the efforts are focused

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on variation operations that can be used to adjust the behaviour of different solutions in light of the performance measure for the given fitness criteria.[40] This process could be used as a starting point for the definition and production of what has become known as the strategy (and/or style) of 'performative' architecture, but, crucially, its open-ended nature also makes it a methodological vehicle capable of incorporating a wider definition of what actually constitutes performance – for instance social, programmatic, conceptual, material, or phenomenological concerns – and allow this to become an active guiding principle in the search for beneficial architectural compositions.

We're interested in creating 'abstract machines'[41] that can be used to produce different effects according to the data fed into them in order to create a wide range of qualities within the resulting architectural structures. Using such constructs, our models can be adjusted in real time according to continuously updated parameters. This makes it possible to build 'fluid' site-specific models that change according to local data and data that changes over time. We currently use a combination of the Grasshopper environment and the Galapagos evolutionary solver plug-in developed by Rutten to achieve this.

Named after Charles Darwin's observations of Galapágos finches – which came to supplant belief in Genesis as well as pre-Darwinian theories of evolution and became crucial for the paradigm shift that allowed Darwin to reach his specific theory of evolution[42] – the Galapagos evolutionary solver natively available within Grasshopper is a component that allows a 'genome' (a range of variables or values that is allowed to change) to be calibrated by small, gradual amounts while keeping track of a number generated by a 'fitness function' and try to make that number larger or smaller over time. Depending on the settings chosen; the process can also be specified to use either an evolutionary solver logic or a simulated annealing method. In this environment, fitness is 'whatever we want it to be'.[43] It changes with our ambitions and preferences and, potentially, with the contextual demands of the situation (as is for instance the case when using data unique to the site). To explain how this idea of fitness can be applied to architecture, Rutten mentions the example of using Galapagos to compose a collection of windows across a façade. In this example, attention needs to be paid to five properties: daylight, sunlight, solar energy, views, and cost. Rutten writes:

> *Some of these properties are (at least partially) linked. A decrease in window area will result both in less direct sunlight, less solar energy and probably less cost. Whereas an increase in window area will result in more daylight and probably better views. Basically we have five forces pulling the solution in different directions.*[44]

That sounds promising, but it should be noted that the method can be demanding in terms of computing power as well as very slow. A single process may run for days or even weeks. Furthermore, there is no guarantee that a solution will actually be found. Unless 'a predefined "good-enough" value is specified, the process will tend to run on indefinitely, never reaching The Answer, or, having reached it, not recognizing it for what it is'.[45] The future possibilities for the application of evolutionary solvers in architecture, however, are exceptional. While Galapagos gives us all we need for the current task, we are still far from exhausting the power of evolutionary algorithms. Evolution in nature works under dynamically changing conditions, with changing optima and optimisation criteria, and the individuals themselves change the structure of the fitness landscape during adaptation.[46] If, for example, the windows in the above example were made from reprogrammable materials fitted on adjustable frames, and connected to an evolutionary solver that in turn was fed live weather data from the site, such non-stationary conditions could be allowed to control the fenestration, potentially providing unrivalled performance.

Two multi-storey timber compromises

Our studio, Ordinary Ltd, is positioned at the intersection of architecture and material science. The practice is based on the insight that humanity's relationship with the matter that makes up our environment has framed our scientific and cultural evolution from the Stone Age to the Silicon Age. Nevertheless, and despite recent scientific advances that open the laboratory doors to a future of material experimentation, we appear to be stuck in the Concrete Age. Our attempts to push architecture into the next material era has given rise to many conjectural (but conceivable) schemes including magnetic skins, bacterial sandstone cities, and buildings made from milk.

The material we have focused most of our energy on to date, however, is wood. As the most prominent of all 100% renewable alternatives, wood is clearly a building material of the future. Possibly consuming less energy than methods involving other materials, timber construction is potentially carbon-negative. Timber serves as a carbon sink by absorbing and binding carbon dioxide – one cubic metre of wood stores nearly one ton of carbon dioxide – and the storage process of carbon dioxide continues inside the wood products throughout their entire life cycles. The production and refining process for timber is also a very energy-efficient one, with more than 75% of the energy used being gained through the burning of forest industry by-products such as woodchips and sawdust. Alternatively, recyclable wood products can either be directly reused, through the simple process of cutting existing boards into new shapes, or burned to use their bio-energy. The carbon returned to the atmosphere during combustion is equal to that absorbed during the growth of the tree – a perfect cycle.[47]

The substitution effect of wood products has a significant impact on the carbon dioxide emissions of the construction industry. The use of wood products replaces other building materials, the

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production of which would have required fossil energy sources.[48] The origin of wood products is easy to trace using extensive certification systems, and timber can be chosen that has been produced in forests that meet the standards of an ecologically, socially, and economically sustainable forest management culture. This environmentally-friendly wood can even be left untreated on the interior, allowing it to continue to breathe and automatically manage the humidity inside a space. Such a material property, wood's capacity for humidity control, shows one of many aspects of timber that can be utilised in a design process based on evolutionary solvers. Cheap and capable of being easily and accurately cut, as well as repaired and worked with comparative ease, wood products are ideal for testing parametric conditions and fabricating the resulting structures using digital-physical processes.[49]

The two following projects are based on a series of operations derived from evolutionary logics that harness the power of using conflict and compromise as strategic tools in the quest for an alternative high-rise timber architecture.

Against the Grain

The eighteen-storey cylindrical mixed-use Against the Grain skyscraper[50] establishes a benchmark for sustainable design in its use of timber as a primary retrofitting material *[5]*. Fulfilling the promise of a disused gasholder, this 'timberscraper' connects to the scale and fabric of its east London site. The scheme focuses on three primary objectives: the sustainable development of a material retrofitting strategy; the programmatic redefinition of a decommissioned structure; and the novel process of using a slotting method together with evolutionary solvers to design a high level of variation within the spatial organisation of the building's interior.

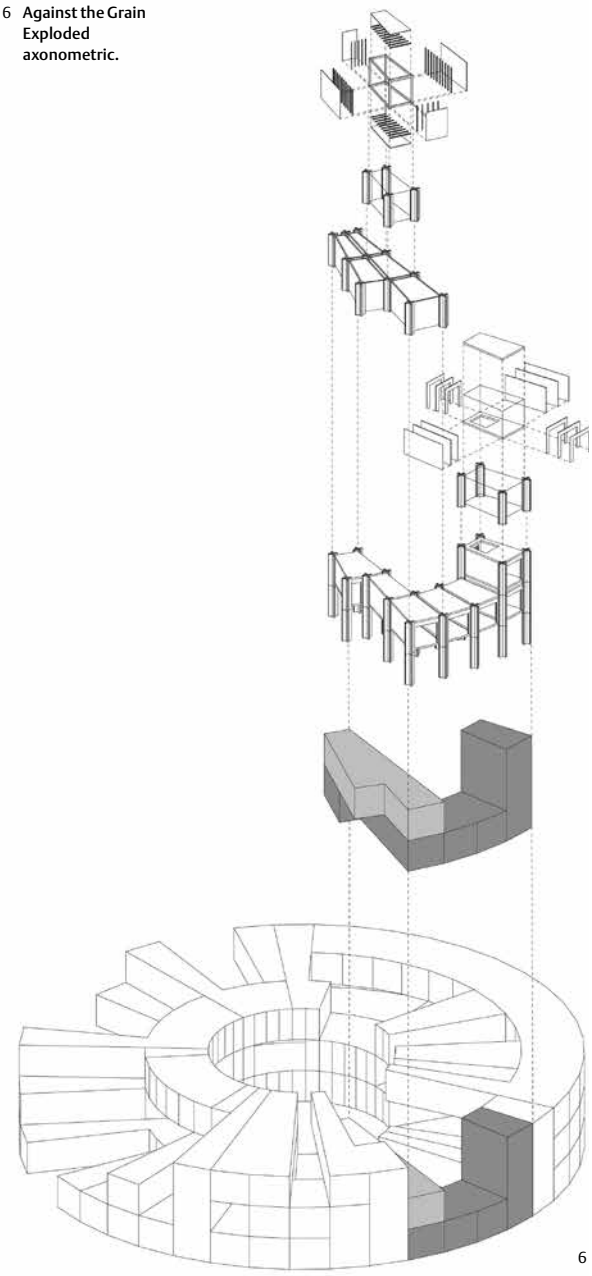
Against the Grain was modelled in Grasshopper in three steps. First, the perimeter of the outer ring of the gasholder, together with a twenty-metre offset, was used to determine the diameter of the central courtyard. The resulting doughnut-shaped plan was divided into fourty-four radial segments, two segments per gasholder bay. Adding three concentric bands (inner, middle, and outer) generated a total of 132 units, each of which was extruded to an individual height of 3.66m and copied upwards twice for a total height of 11m, generating 396 units for each of the gasholder's vertical bands.

For the second step, 'living unit paths' were generated. The three-dimensional centroid of each unit was identified, with each point becoming the vertex of a new mesh. The edges of this mesh described the possible routes through which units could be connected. The number of living units to be created was defined (-x). Initially, the script struggled to resolve more than 20 units, but by randomly selecting (-x) vertices from the inner band of the centroid mesh at any of the three levels, together with a partner vertex from the outer band, the chosen partner vertex could be varied with a slider so as to allow each inner vertex to be combined with any of the outer vertices. A path of shortest distance from the inner vertex to the outer vertex for each pair could then be created, whilst ensuring that this path only followed the edges of the centroid mesh. Using a strategy of stepped progression, we developed a prioritised set of objectives. Galapagos manipulated the outer vertex paired to each inner vertex until the paths created resulted in zero intersections. This was the primary fitness, which ensured that living units never crossed over each other or tried to share units. Once this had been achieved, Galapagos tried to maximise the total length of the paths without creating any new intersections. This was the secondary fitness. For each path, the units intersected by that path were connected (using a boolean operation) to create a joined living unit while the units that weren't intersected became potential 'shared units'. The entire system was then moved vertically by eleven metres and repeated to calculate the next layer of units. A limit of three units in height for each calculation was implemented in order to prevent the creation of very tall living units, while allowing Galapagos to find more efficient solutions (as this rule significantly reduces the number of potential solutions). This could then be repeated to the desired final height of the building. In the present case, there



5 Against the Grain (perspective render). Retrofitting a steel structure with timber.

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6 Against the Grain Exploded axonometric.

are six layers at three floors each, for a total of 18 floors: four contained within the envelope of the gasholder exoskeleton and two above it.

For the third and final step, the position of the shared units was optimised to resolve any unsuitable conditions such as large unsupported and unattainable cantilevers. In the script file, all the shared units were 'turned on' alongside the living units to create a completely solid stack of units. All of these units were then plugged into the Karamba plug-in[51] for loading analysis. Living units were awarded a mass appropriate to their size whilst shared units were given zero mass. This meant that shared units were able to support living units and transfer load from living units to shared units, without contributing any load themselves.

A structural analysis of the system was carried out, again using Karamba, to find the load applied to each shared unit. The shared units with a loading below a certain threshold could then be culled as they performed a negligible structural role. Through this operation, only the shared units supporting key parts of living units remained *[6]*. An alternative method to this latter application could be the use of a gravitational force to the living units, with shared units and other living units being specified as support points. Karamba could then measure the stress for each living unit in the given configuration and Galapagos systematically remove shared units, while constantly re-evaluating the stress in the living units. If a shared unit were culled to produce a large cantilever, this would result in a big increase in the maximum stress. If a shared unit were culled that performed a negligible role, the maximum stress would not be affected. This way, Galapagos could be used to find the arrangement of shared units that provides the best support for the living units.

Beyond Endurance

Bodies within buildings within cities are underused power generators. You and your home are potential power sources that could help buildings shift from being energy consumers to becoming energy producers. The Beyond Endurance project incorporates several innovative strategies, including a novel modular façade component and a highly efficient composting biosystem, to achieve this goal.

According to the Worldwatch Institute, growing prosperity and urbanisation could double the annual volume of municipal solid waste by 2025, challenging environmental and public health management. While some of this waste will eventually be recycled, a doubling of waste would bring the volume of municipal solid waste – including organic material, paper, plastic, glass, metals, and other refuse collected by municipal authorities – from today's 1.3 billion tons per year to 2.6 billion tons.[52] This is largely an issue for the wealthier regions of the world and, one would think, for the architectural community, because that mountain of waste is being generated and disposed of inside buildings before being driven to incinerators and landfills.[53] Surely optimising the engineered flows of waste products should be at least as interesting as designing favourable circulation paths for human agents through our built environment? Roughly a quarter of the world's garbage is diverted to recycling, composting, or digestion – environmentally superior waste management options. That figure is not even close to being sustainable, and the present proposal is an attempt at offering a new solution that doesn't just deal with the 'problem' of waste but offers the opportunity of turning it into a driver for environmental, financial and societal gains.

Beyond Endurance is an energy-producing, mass-customised, scalable building typology made from wood that can be constructed as a single-family house or a multi-storey skyscraper (the larger structure is 60 metres tall) *[7]*. The building is *siteless* in that it can be erected almost anywhere in the world and also exceptionally *site specific* in that it incorporates optimisation algorithms that control

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the axial directionality of the building elements so as to create optimal conditions for harvesting renewable energy from its particular and unique site. Part of that renewable energy is derived from the inhabitants themselves, as food waste and 'humanure' are fed into composts inside the vertical towers, where they are turned into heat, biogas, and manure. Some of that energy is then fed back into the greenhouses that sit on top of each living unit, making it possible for the inhabitants to remain largely self-sufficient in terms of food. Surplus produce is offered to the local community and surplus energy is sold back to the grid. The building's small footprint provides a remarkable ratio of liveable space and energy production to ground area. The towers act as structural and circulation cores while a unique modular façade component harvests rainwater plus solar and wind energy.

Evolutionary solvers were predominantly used during three parts of the design process, to optimise the positioning of composting towers, as well as the populating of facade components onto those towers *[8]*.

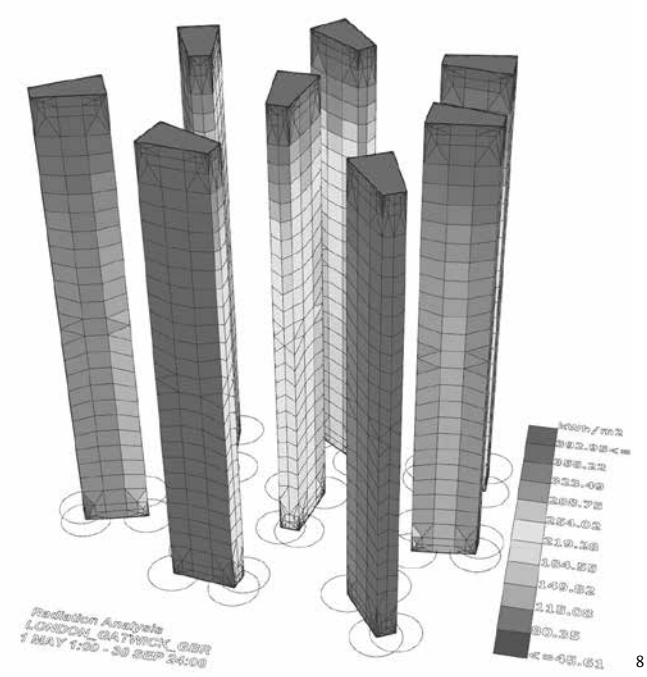
The tower design process was based on a custom Grasshopper definition that specified the site boundary and then populated this with a number of curves equal to the desired number of composting towers. The position and orientation of each curve could be independently controlled using sliders. The curves were extruded to the desired tower height, after which a solar radiation simulation was applied for the given location and for a defined period of time. Galapagos was then allowed to manipulate the position and orientation of the towers to maximise the total solar radiation falling on all of them. The tower base curves were then offset to create tower plan outlines, which were extruded to get the tower volumes, the surfaces of which were divided into a grid of quads, or panels, with a maximum size of 1,200 x 1,500mm.

The design of the component base geometry started by isolating four corner points of such a generic quad, copy the top corners perpendicular to the panel by 250–1,000mm (a slider-controlled value). These new points were then copied perpendicular to the panel by 0–1,000mm and downwards by up to 75% of the panel height (both values again controlled using sliders). Connecting the points with mesh faces created the component.

To populate the components onto the towers, the centre point of each tower face was located, and the ten panels closest to this point (for each face) identified. Each of these panels was then populated with the component base geometry. While we are interested in optimising for performance, we are also keen to provide buildable solutions, and so decided to make the ten components on each face be controlled by the same slider values (that is, identical) while allowing components to vary between faces. By using ten components instead of one, any overshadowing issues should be addressed in the optimisation. Galapagos was then used to manipulate the geometry of the components in order to maximise the solar radiation falling on their solar panel face. Finally, the components were mapped to every panel of the tower, and any components that intersected the living units culled.



7



8

7 Scalably sustainable. The larger version of Beyond Endurance is envisaged to rise 60 metres above ground.

8 Beyond Endurance. Evolutionary solvers controlling the positioning of the towers within the site envelope.

The resistance of negotiation

Equilibrium is the condition of a system in which all competing influences are balanced, and a mechanical equilibrium is a state in which a momentum coordinate of a particle, rigid body, or dynamical system is conserved.[54] This concept is crucial to engineering as a body in equilibrium experiences no acceleration and, unless disturbed by an outside force, will remain in equilibrium

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indefinitely.[55] It has been shown that the use of evolutionary logics inspired by biologic phenomena to adjust the relative importance of objectives in conflict allows for a new conceptual vehicle to be introduced to the world of contemporary architecture. This vehicle – based on a different equilibrium to the traditional, mechanical one – is that of the compromise. To paraphrase US writer Charles Hoy Fort, all biologic phenomena act to adjust: there are no biologic actions other than adjustments. Adjustment is another name for compromise. Compromise is the universal, or that which has nothing external to derange it.[56] Our compromise is a conceptual-practical equilibrium, a system capable of optimising for the important stuff. Whatever that is.

Key to such a reappraisal of the general perception of the compromise, at least in the area of moral principles, as being an inherently negative, if not downright evil, force[57] is the creation of entire ecosystems of architectural variations on an initial theme. As the author and *Economist* correspondent Andreas Kluth explains, evolution means:

> *a) that living organisms constantly reproduce with variations, b) that some of those variations will be more adapted to their environment than others and therefore reproduce more, leading c) to new species, which in turn split into yet more species, until d) entire ecosystems come about, constantly in flux and consisting of uncountably many organisms, all feeding off one another.*[58]

Our thesis is that controlling such reproduction with variation within an architectural context is key to finding new and better possibilities (as opposed to singular 'solutions') for the development of a more sustainable, responsible, efficient, and beautiful built environment.

There is a tendency in the building industry to fear added *complexity* when really the concern is, or should be, about wasting time on *complicated* processes.[59] Many people still get the complex mixed up with the complicated and use the words interchangeably. To give an example of something that is complex without being complicated, 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. In the systems theory literature, 'complicated' often refers to something with many parts, whereas 'complex' refers to an unpredictable, emergent behaviour. The present study outlines a *resistance* against this misconception on the part of the commercial powers operating in the built environment and offers a method for adding valuable complexity to that environment in a quantifiable and potentially highly beneficial way, regardless of whether the ambition is to do with making more money or attempting to save the planet one building at the time. We hope that future studies will provide a deeper understanding of the plethora of forms and structures that such a *resistance of negotiation* might take and how it might be defined, communicated, and used constructively as an architectural design tool.

Notes

1. John Frazer, *Themes VII: An Evolutionary Architecture* (London: AA Publications, 1995).
2. For a good outline of the evolutionary logic on which Galapagos is based, see David Rutten's blog post 'Evolutionary Principles Applied to Problem Solving', a postscript based on his lecture given at the AAG10 conference in Vienna on 21 September 2010. Available online: <http://www.grasshopper3d.com/profiles/blogs/evolutionary-principles> (accessed 12 August 2015).
3. Louis H. Sullivan, 'The Tall Office Building Artistically Considered', in *Lippincott's Magazine*, March (1896), pp. 403–9, available online: <https://archive.org/details/tallofficebuildioosull> (accessed 12 August 2015).
4. Ayn Rand, *The Fountainhead* (Indianapolis: Bobbs Merrill, 1943).
5. Rutten, 'Evolutionary Principles'.
6. This is a simplified example. In real life, a plethora of different aspects converge to achieve fitness relative to the resources available: 'Charles Darwin made two seminal contributions to evolutionary science. The first was the recognition that no two individual animals are alike: they are not perfect copies. Darwin's other related contribution was the idea of natural selection. In a nutshell, natural selection suggests that, because resources are finite, and because of random variation, some individuals will be better than others at accessing those resources. That variant will then gain enough of an advantage that it will produce more surviving offspring than other individuals belonging to the same species. Biologists refer to this advantage as an increase in an animal's "fitness".' Bernard Wood, *Human Evolution: A Very Short Introduction* (Oxford: Oxford University Press, 2005).
7. 'We are survival machines – robot vehicles blindly programmed to preserve the selfish molecules known as genes.' Richard Dawkins, *The Selfish Gene: 30th Anniversary Edition* (Oxford: Oxford University Press, 2006), preface to the first edition (1976).
8. The most famous example of how such a 'lean' system can deliver exceptional results is from the car industry: from 1902, when Toyota founder Sakichi Toyoda began implementing the concept of Jidoka (building in quality at the production process as well as enabling separation of man and machine for multi-process handling). See: Yasuhiro Monden, *Toyota Production System* (Norcross, GA: Industrial Engineering and Management Press, 1993); Shigeo Shingo, *A Study of the Toyota Production System from an Industrial Engineering Viewpoint (Produce What Is Needed, When It's Needed)* (Cambridge: Productivity Press, 1989); Taiichi Ohno, *Toyota Production System: Beyond Large Scale Production* (Cambridge: Productivity Press, 1988); Jeff Liker, *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer* (New York: McGraw-Hill, 2004); also the summary published by the Art of Lean website as the Toyota Production System Basic Handbook, available online: <http://www.artoflean.com/files/Basic_TPS_Handbook_v1.pdf> (accessed 12 August 2015).
9. At its core, the system we describe has been developed to find what Simon would call 'satisficing'

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(good enough) decisions. Even Darwin's 'natural selection only predicts that survivors will be fit enough, that is, fitter than their losing competitors; it postulates satisficing, not optimising'. Herbert Simon, *Models of My Life* (Basic Books, Sloan Foundation Series, 1991), p. 166.

10. Herbert Simon, 'Rationality in Psychology and Economics', in *Journal of Business*, Part 2: *The Behavioral Foundations of Economic Theory*, 59:4 (1986), pp. 209–224.
11. '[...] the "bearing of weight" is not simply a constructive problem, but also a challenge for the construction of meaning.' Nader Tehrani, 'Foreword: A Murder in the Court', in *Strange Details*, ed. by Michael Cadwell (Cambridge MA: The MIT Press, 2007), p. viii.
12. While we realise a cybernetics enthusiast would rejoice in the use of such an almost-ironic feedback loop – that is, a representative of a field outside of the profession explaining to architects how to do architecture – the British software engineer and author Martin Fowler, in a now-classic 'white paper', discusses several definitions of the term 'software architecture', putting forward the following suggestion: 'Architecture is about the important stuff. Whatever that is.' Despite not being about 'architecture' in the traditional, pre-computer age sense, Fowler's elucidation is a concise illustration of the strategic aspects of the evolutionary architecture model. Martin Fowler, 'Who Needs an Architect?' (White Paper, IEEE Software, September 2003), available online: <http://martinfowler.com/ieeeSoftware/whoNeedsArchitect.pdf> (accessed 12 August 2015).
13. Thomas Reid, *Essay: Of the Phenomena of Nature* in *Essays on the Active Powers of Man* (London: John Bell, and G. G. J. & J. Robinson, 1788), p. 47.
14. Steven Holl, 'Questions of Perception: Phenomenology of Architecture', in *Questions of Perception: Phenomenology of Architecture*, eds. by Steven Holl, Juhani Pallasmaa, Alberto Pérez-Gómez (San Francisco: William Stout Publishers, 2006), p. 41.
15. Ibid., p. 42.
16. Ibid.
17. For an introduction to multi-objective optimisation, see Ching-Lai Hwang and Abu Syed Md Masud, *Multiple Objective Decision Making, Methods and Applications: A State-of-the-Art Survey* (Berlin: Springer, 1979).
18. Having made this observation, henceforth we will assume that the notion of the 'optimal' refers to this reading of the optimal as being per definition asymptotic.
19. Simon, *Models of My Life*, p. 361.
20. cf. William Provine, *Sewall Wright and Evolutionary Biology* (Chicago: University of Chicago Press, 1986).
21. 'Frontline systems, Basic Solver – Evolutionary Solving Method Stopping Conditions' (website entry), available online: http://www.solver.com/content/basic-solver-evolutionary-solving-method-stopping-conditions (accessed 12 August 2015).
22. Alan Turing, 'Intelligent Machinery: A Report by A. M. Turing', submitted to the National Physical Laboratory in 1948. Reprinted in *The Essential Turing*, ed. by B. J. Copeland (Oxford: Oxford University Press, 2004), p. 409. A digital facsimile of the original manuscript is available online at: <http://www.alanturing.net/intelligent_machinery/> (accessed 12 August 2015).
23. Ivan Garibay, 'Evolutionary Computation', EEL 4818H (2008), p. 1.
24. D. H. Wolpert and W. G. Macready, 'No Free Lunch Theorems for Optimization', in *IEEE Transactions on Evolutionary Computation*, 1:67 (1997), pp. 67–82, available online: <http://ti.arc.nasa.gov/m/profile/dhw/papers/78.pdf> (accessed 12 August 2015).
25. cf. Lawrence J. Fogel, *On the Organization of Intellect* (PhD Thesis, University of California, Los Angeles, 1964).
26. Gary B. Fogel et al., 'Evolutionary programming', *Scholarpedia*, 6:4 (2011), p. 1818, available online: <http://www.scholarpedia.org/article/Evolutionary_programming> (accessed 12 August 2015).
27. David B. Fogel and Kumar Chellapilla, 'Revisiting Evolutionary Programming', pp. 1–2, available online: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.53.8217&rep=rep1&type=pdf> (accessed 12 August 2015).
28. Ibid., p. 2.
29. Ibid.
30. Le Corbusier, *Towards a New Architecture*, trans. by Frederick Etchells (London: The Architectural Press, 1927).
31. Thomas Bäck, Ulrich Hammel, Hans-Paul Schwefel, 'Evolutionary Computation: Comments on the History and Current State', in *IEEE Transactions on Evolutionary Computation*, 1:1, April (1997), p. 3.
32. Fogel, Chellapilla, 'Revisiting Evolutionary Programming', p. 2.
33. Ibid., p. 6.
34. Fogel, *On the Organization of Intellect*.
35. Richard Dawkins, *The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe Without Design* (New York: Norton & Company, 1986). This book came with a small computer program that generated a seemingly infinite stream of 'bio-morphs' based on human selection.
36. Rutten, 'Evolutionary Principles'.
37. Garibay, 'Evolutionary Computation', p. 3.
38. Bäck, Hammel, Schwefel, 'Evolutionary Computation', pp. 4–5.
39. Ibid.
40. Fogel and Chellapilla, 'Revisiting Evolutionary Programming', p. 6.
41. 'The diagrammatic or abstract machine does not function to represent, even something real, but rather constructs a real that is yet to come, a new type of reality.' Gilles Deleuze and Félix Guattari, *A Thousand Plateaus*, trans. by Brian Massumi (London: Athlone Press, 1988), p. 142.
42. More than a most eminent naturalist, Darwin was also a prototypical empirical scientist, inductively deriving his theory of evolution based on empirical evidence rather than on theoretical, or even metaphysical or religious grounds. During his famous voyages, Darwin assembled a huge collection of animal-specimens, which contributed to the theory that changed our view of life. The 'Darwin Finches' were a group of about fifteen species of passerine birds, unrelated to the true finches, which Darwin collected on his second voyage of HMS *Beagle* (27 December 1831–2 October 1836). The most important differences between species are in the size and shape of their beaks, and the beaks are highly adapted to different food sources. See David Lack, *Darwin's Finches* (Cambridge: Cambridge University Press, 1947). Reissued in 1961 by Harper, New York, with a new preface by Lack; and in 1983 by Cambridge University Press with an introduction and notes by Laurene M. Ratcliffe and Peter T. Boag. See also Momme von Sydow, 'Survival of the Fittest' in Darwinian Metaphysics: Tautology or Testable Theory?' in *Reflecting on Darwin*, eds. by E. Voigts, B. Schaff, M. Pietrzak Franger (London: Ashgate, 2014), pp. 199–222, from which the above note is largely derived.
43. Rutten, 'Evolutionary Principles'.
44. David Rutten, 'Define "Fitness"...' blog post, *I Eat Bugs for Breakfast* (7 March 2011), available online:

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<http://ieatbugsforbreakfast.wordpress.com/2011/03/07/define-fitness/> (accessed 12 August 2015).

45. Rutten, 'Evolutionary Principles'.
46. Bäck, Hammel, Schwefel, 'Evolutionary Computation', pp. 11–12.
47. Lloyd Alter, 'FMO Tapiola: Prefab Wood Office Building in Finland', available online: <http://www.treehugger.com/modular-design/fmo-tapiola-prefab-wood-office-building-in-finland.html> (accessed 12 August 2015).
48. 'The effect of product substitution is calculated as the difference between the fossil emissions associated with the life-cycle of wood products and the avoided fossil emissions associated with the non-wood products that are not used. In all cases except one (wood fibre insulation panel vs. mineral wool insulation), the substitution effect is beneficial, i.e. the life cycle fossil emissions of the wood product are lower than those of the non-wood product.' Roger Sathre and Jennifer O'Connor, *A Synthesis of Research on Wood Products & Greenhouse Gas Impacts*, 2nd edn (Vancouver, BC: FPInnovations, 2010); Technical Report No. TR-19R, ISBN 978-0-86488-546-3), p. 81.
49. Christopher Beorkrem, *Material Strategies in Digital Fabrication* (Oxford: Routledge, 2013), p. 14.
50. Alex Kaiser, Magnus Larsson, Ulf Arne Girhammar, 'Against the Grain: Redefining the Living Unit – Advanced Slotting Strategies for Multi-Storey Timber Buildings' (WCTE 2014), available online at: <https://pure.ltu.se/portal/files/100226820/ABS720_Kaiser_web.pdf> (accessed 12 August 2015).
51. Karamba is 'an interactive, parametric finite element program' that lets users 'analyze the response of 3-dimensional beam and shell structures under arbitrary loads'. See: <http://www.food4rhino.com/project/karamba/?etx> (accessed 12 August 2015).
52. Gary Gardner, 'Municipal Solid Waste Growing', available online at http://vitalsigns.worldwatch.org/vs-trend/municipal-solid-waste-growing (accessed 12 August 2015).
53. Geographical differences abound. In 2012, Sweden announced that its shortage of waste was driving the country to import an annual 800,000 tons of garbage from its neighbour, Norway, in order to fulfil its waste-to-energy needs. Norway of course paid Sweden to take care of its waste, in effect meaning the Swedes made money from getting a free supply of energy. Stephen Messenger, 'Sweden to Import Garbage as Trash Supplies Run Dry', available online: <http://www.treehugger.com/energy-efficiency/sweden-import-garbage-trash-supply-runs-dry.html?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+treehuggersite+%28Treehugger%29> (accessed 12 August 2015).
54. John L. Synge and Byron A Griffith, *Principles of Mechanics,* 2nd edn (New York: McGraw-Hill, 1949), pp. 45–6.
55. Encyclopædia Britannica Online, s. v. 'equilibrium' (6 November 2014), available online: <http://www.britannica.com/EBchecked/topic/190745/equilibrium> (accessed 12 August 2015).
56. Charles Hoy Fort, *The Book of the Damned* (New York: Boni and Liveright, 1919), p. 14. We have changed the word 'equilibrium' to 'compromise'.
57. 'In any compromise between food and poison, it is only death that can win. In any compromise between good and evil, it is only evil that can profit. In that transfusion of blood which drains the good to feed the evil, the compromise is the transmitting rubber tube.' Ayn Rand, *Atlas Shrugged* (New York: Random House, 1957), p. 965.
58. Usually we call this diversity, rather than complexity, which we consider to be good not only in the sense of being colourful but also of being stable, writes Kluth, before noting that 'We do not say, for example, that a given ecosystem has too many "points of failure", as a computer system might. The opposite is the case. If any link among the ecosystem's uncountable permutations fails, another connection replaces it. There are redundancies. The ecosystem is self-correcting.' And moving on to consider an individual in this system: 'From the point of view of [...] an ant, say [...] the ecosystem might look Hobbesian in that life is probably poor, solitary, nasty, brutish and short. Well, not solitary, perhaps. (But the ecosystem did not evolve for the ant anyway. It didn't evolve for anything. It evolved because it could not not evolve).' Andreas Kluth, 'Man v Nature Simplicity Misunderstood', blog post (2010), available online: <http://andreaskluth.org/2010/05/26/man-v-nature-simplicity-misunderstood/> (accessed 12 August 2015).
59. Hannah Wood and Kassim Gidado, 'Project Complexity in Construction', in *The International Construction Conference, Royal Institute of Chartered Surveyors, RICS COBRA. RICS Foundation UK* (Dublin: Ireland, 2008. ISBN 9781842194348), available online: <http://core.kmi.open.ac.uk/download/pdf/9552740.pdf> (accessed 12 August 2015).

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Alex Kaiser is a co-founder and director of Ordinary Ltd. A teacher at his own *alma mater*, the Architectural Association, since 2009, Kaiser is an educator with a particular interest in the exploration of drawing and painting in architecture, as well as a penchant for the art and science of growing crystals. He lives in London.

Ulf Arne Girhammar is an engineering professor at the Luleå University of Technology (LTU). Girhammar specialises in multi-storey timber structures, and supervised Larsson and Kaiser throughout their licentiate degree studies in 2014.

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