

A Consideration of the Zoetic Engineering Grand Challenge

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Abstract. The Zoetic Engineering Grand Challenge is a proposal to catalyze work in the field of Cyber-Bio-Physical Systems by attacking the goal of creating a Living Skyscraper. This work builds upon that original idea, introducing the concept of the Zoetic Arcology: a proposal for how the tools of Artificial Life can be applied to the creation of a self-building and self-sustaining alternatives to conventional urban environments. The underlying design philosophy of this concept will be outlined, drawing from the ideas of Arcology and Reconciliation Ecology, followed by a discussion of how it could be implemented from an engineering perspective: investigating possible theoretical, technological and scientific frameworks that could be leveraged; pathways to the design and development of the structure; the requirements of that structure's starting point; how to implement the concept of growth in an artificial physical system; and what raw materials & energy generation methods might be utilised. Finally, a road map of future research is outlined.

Keywords: Zoetic Systems, Zoetic Engineering, Cyber-Bio-Physical Systems, Artificial Life, Bio-inspired Architecture, Arcologies, Morphogenic Systems, EvoDevo, Evolutionary Developmental Systems, Evolutionary Design, Digital Twins, Design Automation, Insect Hives, Automated Construction, Living Buildings, Reconciliation Ecology, Rammed Earth Construction, Artificial Sandstone, Biorock, Landfill Reclamation, Material Reuse, Electronics Upcycling, Sustainable Energy Generation

1 Introduction

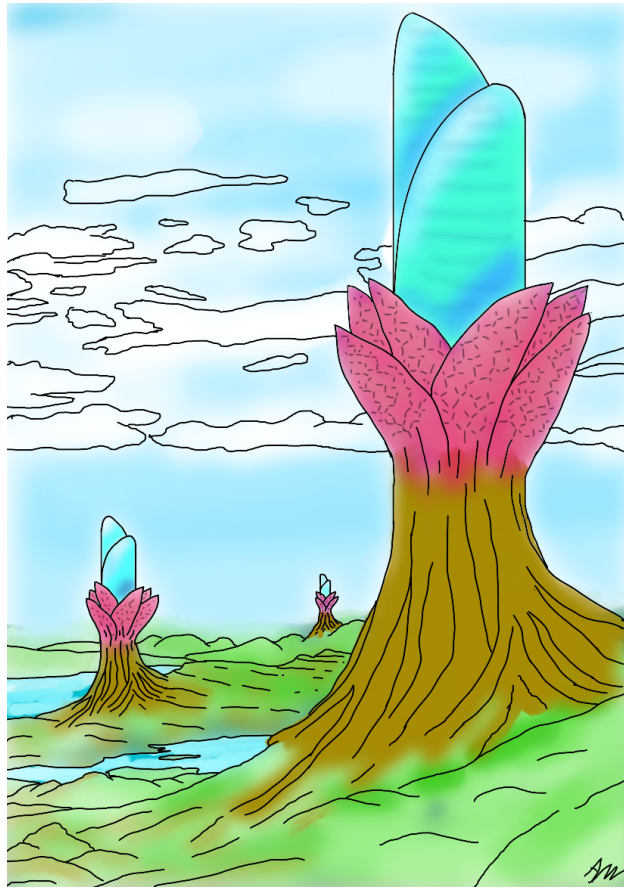


Figure 1: An artistic depiction of the Living Skyscraper proposal, author's own work.

At the ALife 2024 conference in Copenhagen, representatives of this community were treated to a talk by that year's ISAL Lifetime Achievement award winner, Professor Susan Stepney. Her talk "Life as a Cyber-Bio-Physical System" built on work discussed previously in Genetic Programming Theory and Practice XIX (Stepney, 2023), arguing that a true understanding of living or lifelike systems called for a unification of Computational, Biological, and Physical sciences in order to study "self-producing far-from-equilibrium systems embodied in smart functional metamaterials with non-trivial meta-dynamics". In place of the unwieldy and somewhat overly broad *Cyber-Bio-Physical Systems*, Professor Stepney suggested that such phenomena can be refereed to by the more elegant term *Zoetic Systems*, meaning "of or relating to life" (Merrian-Webster, 2024). Of specific interest to this author

however is that Professor Stepney suggested that this nascent domain might be catalysed through the adoption of an Engineering grand challenge: a Living Skyscraper, visualised in figure 1.

This work seeks to build upon this proposal by introducing the Zoetic Arcology: a self-building, self-sustaining habitat intended to serve as an alternative to conventional urban environments. A synthetic ecology, intermeshed with and qualitatively enhancing both the existing natural local that it sits within, as well as the species that inhabit it, humans included. This paper will outline the architectural philosophies underpinning this concept, Arcology and Reconciliation Ecology; before providing an exploration of a means by which it could be realised through the application of digital-twin based gardening; human-in-loop cyber-physical co-evolution; the hybridisation of Exogenous and Endogenous growth; and the exploitation of abundant naturally occurring materials & the reclamation of waste ones.

1.1 Motivations

The first motivation for pursuing this project is the one alluded to previously: by undertaking a non-trivial engineering challenge that leverages the phenomena encapsulated by the idea of Zoetic Systems, our understanding of those systems can be increased and new tools and techniques for working with them will arise. The other motivation is one shared by many other fields of research at this time: environmental concerns. As the human population expands, so to does the area of land which is occupied by our preferred habitats in the form of towns, cities etc. The expansion of these urban areas is one of the primary drivers of the loss of the habitats of other species, and the reduction of biodiversity (Simkin et al., 2022); this even before factoring in the impact of meeting urban area's needs for energy (International Energy Agency, 2024), or the impacts of the construction of new conurbations (Horvath, 2004). In the effort to combat these growing demands, much inspiration has been taken from the natural world, where large structures grow and maintain

themselves on much smaller pools of raw materials and energy.

The application of the principles of biology to the field of architecture is nothing new, with Ripley and Bhushan (2016) asserting that bioinspiration can be seen as far back as 12th century European Cathedrals. More contemporary examples span from the aesthetic, such as the Lotus Temple in New Delhi, India (Bahá'ís of India, 2024); to the functional, like the Eastgate Center in Harare, Zimbabwe, whose passive ventilation system is inspired by Termite mounds (Pearce, 2016). More recently ideas such as Morphogenetic Architecture or Evolutionary-Developmental (Evo-Devo) design have emerged, which go a step beyond cribbing directly from existing forms by instead growing the design of structures through the application of idea like models of tissue growth (Hensel et al., 2004, 2006; Roudavski, 2009). While research in the simulation domain has produced some promising results, such as the work of Richards et al. (2012), very few examples of this approach have been put into practice, overwhelmingly in the designing of the aesthetic elements of a structure, with the actual translation into a viable structure being handled by conventional engineering. Furthermore, while experiments have been carried out on the use of Morphogenic Systems to tackle engineering problems, there is no coupling between the morphogenic model and a conception of how the structure might be built (Kowaliw et al., 2007).



Figure 2: The Water Cube, the Olympic/Paralympic aquatics center in Beijing, China (Wikimedia Commons, 2010b)

Roudavski (2009) in particular cites *The Water Cube*, the aquatics centre built for the 2008 Olympics/Paralympics in Beijing, China. The building was created by subtracting the interior volumes from a simulation of a soap-bubble-like geometry known as a Weaire–Phelan Structure, which yielded its distinctive cellular appearance. Roudavski notes however that “[the] project also misses an opportunity because it does not utilize the potential of its bubble-like structure to adapt to environmental conditions or other criteria. While it might be that The Water Cube project had no need for adaptability, in other circumstances, this potential can be beneficial. In contrast, many cellular structures in nature are highly adaptable and, therefore, can suggest further development for their architectural counterparts” (Roudavski, 2009). A sentiment sure to resonate with the Artificial Life community.

While biological inspiration is of great interest to this work, it is important to avoid taking nature as the primary source of truth. Life-as-it-could-be not life-as-it-is. Therefore, it is necessary to lay a different philosophical foundation, one that is oriented towards the ends and is more permissive in its scope of means. This foundation for the Zoetic Arcology is built upon two existing ideas: Arcology and Reconciliation Ecology.

2 Philosophy

2.1 Archology

To most individuals, the term Arcology conjures a specific image: a single monolith building housing many hundreds of thousands of people, often nebulously “self-sufficient” in some fashion, and almost always depicted as either a brutalism adjacent monolith or a glass clad geometry exercise; an image perhaps best encapsulated in recent years by the THE LINE mega-city project currently underway in Saudi Arabia (NEOM, 2025). However, by returning to the origin point of the term a much more intriguing vision emerges. Coined by the architect Paolo Soleri as a portmanteau of Architecture and Ecology, though dis-

tinct from the modern use of the term Architectural Ecology, which refers to idea more in line with the next section, he describes the concept thus: "Arcology is intensively ecological and because of its self-containment is able to be integrally accepted by the natural ecology ... Arcology is the name adopted to identify a structure which is (somehow) a three-dimensional landscape or topography. In it ... are organised the private and public institutions that go into making any urban center worthy of the term. Arcologies are architectural organisms of such character and dimensions as to be ecologically relevant" (Soleri, 1973). The difference between popular conception and the original idea of an Arcology can be further shown with Soleri's own attempt to realise his concept: Arcosanti, shown in figure 3.



Figure 3: A view of Arcosanti from the southeast (Wikimedia Commons, 2017)

With construction starting in 1970 and with additions continuing to be made even after Soleri's death in 2013, Arcosanti serves primarily as an educational center as well as an ongoing experiment/demonstration of the idea of an Arcology as an ecologically harmonious habitation, as much a part of the landscape it rests within as said landscape's natural elements (Cosanti Foundation, 2024). While Arcosanti is not a living structure in the sense

that the ALife community would use the term, Soleri's conception of an architectural organism accepted by the surrounding landscape in a symbiotic fashion is of clear utility here.

2.2 Reconciliation Ecology

Reconciliation Ecology, coined in Rosenzweig (2003), espouses the philosophy that alongside the preservation of existing natural habitats and the reclamation of ones that have been lost, the way in which our human habitats are designed and built can be done to encourage biodiversity within them without compromising, and in some cases improving, their habitability for us. Green roofs, where a building's uppermost surfaces are used to grow various plants, are an often cited example; as they promote increased biodiversity compared to conventional materials, improves the building's thermal performance and helps to manage rainfall (Wooster et al., 2022). The use of plants for the treatment of waste water has similar potential, being a mature technology that combines a necessary component of infrastructure with an opportunity for animal and plant species to thrive (Cooper & Green, 1995; Glenn et al., 2009).

This concept also extends to the non-living aspects of urban design. Research into the species that dwell in urban hardscapes (such as walls) shows that, despite the stresses of the anthropocentric environment seeming to demand hardy specialists, these areas are in fact colonized by native plant species adapted to natural rock outcrops (Larson et al., 2000); with a similar phenomena occurring with insect populations in industrial sites (Eversham et al., 1996). This indicates that if the morphology of our built environment is designed to be harmonious with the natural environment that it is to sit within, native species will naturally come to colonise it.

2.3 The Zoetic Archology

Let us synthesis these various perspectives together. Reconciliation Ecology asserts that an urban environment can be made a haven for plant and animal species if the morphology of said environment echos its natural counterpart, thus ingratiating the two. Arcology states that architecture achieves ingratiating with the local landscape when the urban environment is conceptualised as a living organism in its own right. The Zoetic Grand Challenge seeks to create living structures for human habitation.

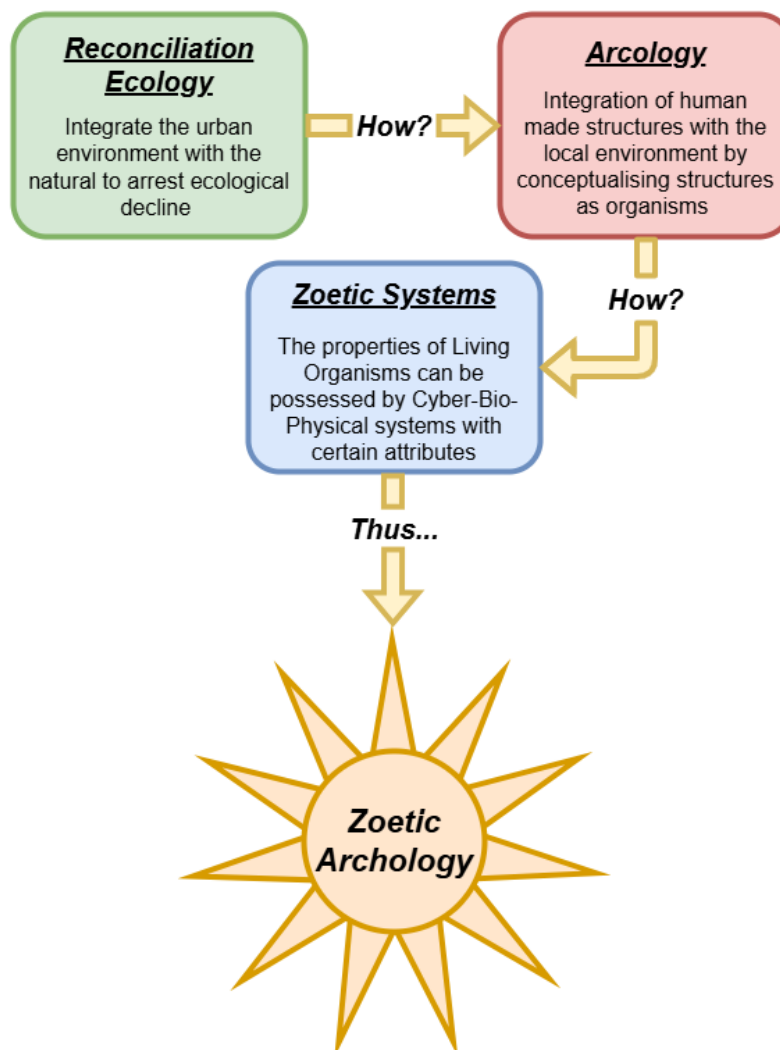


Figure 4: An illustration of the synthesis of the elements of the philosophy of the Zoetic Archology

So, we make the following assertion: Through the application of the principles of Artificial Life, it is possible to create an urban ecosystem that is able to grow and maintain itself; which also co-exists harmoniously alongside & within its natural counterparts on both a biological & landscape level; comprised of an artificial, living substrate that supports a mixture of artificial (whether born of mechanical or biological engineering) and natural species; that together are able to realise all of the necessities for human habitation, while also offering a place in which other species can also thrive.

With this high-minded end goal set forth, let us step back and begin considering the nuts and bolts of growing an artificial structure in the first place, starting with a question of said structure's design. Or rather the acceptance of a lack thereof.

3 Gardening by Digital Twin

Modern conventional construction demands a high degree of certainty as to what is to be undertaken before the first spade hits dirt; something that Zoetic systems, with their complex and highly stochastic behaviours, cannot provide. Envision the dissatisfaction one would face having to explain that a new motorway will be delayed as it decided to grow a slip road in an undesirable direction. However, being overly prescriptive with the design of a hypothetical Zoetic structure runs a risk of robbing us of the very advantages we are seeking to gain. Considering again the motorway example, if the exact route taken was fixed, the ability of the growth process to take optimal advantage of the terrain or navigate around unaccounted for obstacles would be negated.

This dichotomy speaks to a conflict that often occurs when seeking to apply autonomous mechanisms of any sort, not just those with an ALife heritage, to practical problems: both with regards to ensuring a system does what is wanted, but more importantly to ensuring a system doesn't do something harmful. And while means to address this dichotomy do exist, such as the application of Formal Methods to provide mathematical guaranties of

a systems possible states (Wongpiromsarn et al., 2023), many of them assume a system whose possible states are manageably finite. Something that cannot be said for many kinds of conventional construction projects, let alone Zoetic Systems.

A resolution to this conflict, comes in the form of the gardening metaphor for system design. Even following the advent of genetically modified organisms, it is still not possible for a person to impose an exact morphology on a living plant, let alone upon the collection of plants that comprise even a small garden. Instead, horticulturalists place plants in certain locations to yield broad garden structures; train them along supports to guide their individual growth; prune away damaged or unwanted growth; and even adjust the other organisms within the environment by seeking to remove pests or encourage pollinators. Applying these sort of principles to artificial systems is an idea that has been articulated by many in the ALife community, but for the purpose of this work we will start with Julian Miller's discussion of the concept in Miller (2018). Building on previous work on evolving cellular automata using CPG (Miller & Thomson, 2004), Miller's Software Garden was a visual programming environment where programs would be constructed through the manipulation of developmental systems. The process would start with a genotype Seed, which is then implanted within an environment and allowed to grown its corresponding phenotype. The programmer would then observe this growth and make alterations to the phenotype such that the resulting growth produced a desired outcome. Taking this idea a step further, Stepney et al. (2019) discuss applying this idea to the construction of material objects, with different components of a final object (such as the skeleton, electrical services, plumbing etc for a building) would come from different Seeds planted together, their growth patterns being affected by each other, the environment, and gardener interventions to finally yield the desired form.

However, in brining this concept out of the world of software and into the physical domain, a number of practical limitations emerge: gardening actions must be embodied in some

fashion (how would one prune a section of roadway or train an electrical cable?) and come at a material cost. Even if we assume the system is able to use/reuse raw materials with perfect efficiency and recycle pruned components, a cost will always be incurred in time & energy. The answer is to adopt a hybrid approach: a cyber-physical structure that grows within both the physical world and a virtual counterpart at the same time. Furthermore, we can set this method on a strong foundation by drawing from ongoing work outside the ALife space: Digital Twins. Though the idea has older origins, digital-twins as they are now date from NASA work in the 2010s, they originally used the term Virtual Digital Fleet Leaders (VDFLs) (Council, 2012). A digital-twin is a computational model of a real world system, intended to be accurate enough to stand in for said system for purposes such as testing. The crucial difference between a digital-twin and a standard computer model however is that the twin is connected to its real world counterpart through various sensors and data loggers (Haag & Anderl, 2018). This allows the not only the state of the digital-twin to be updated as changes occur in the real world, but the real world systems responses to stimulus can be used to refine the model used by the digital-twin. Thus, when the model is used to dry run alterations to its physical counterpart, such as repairs or upgrades, it is a close to the current state of that counterpart as possible.

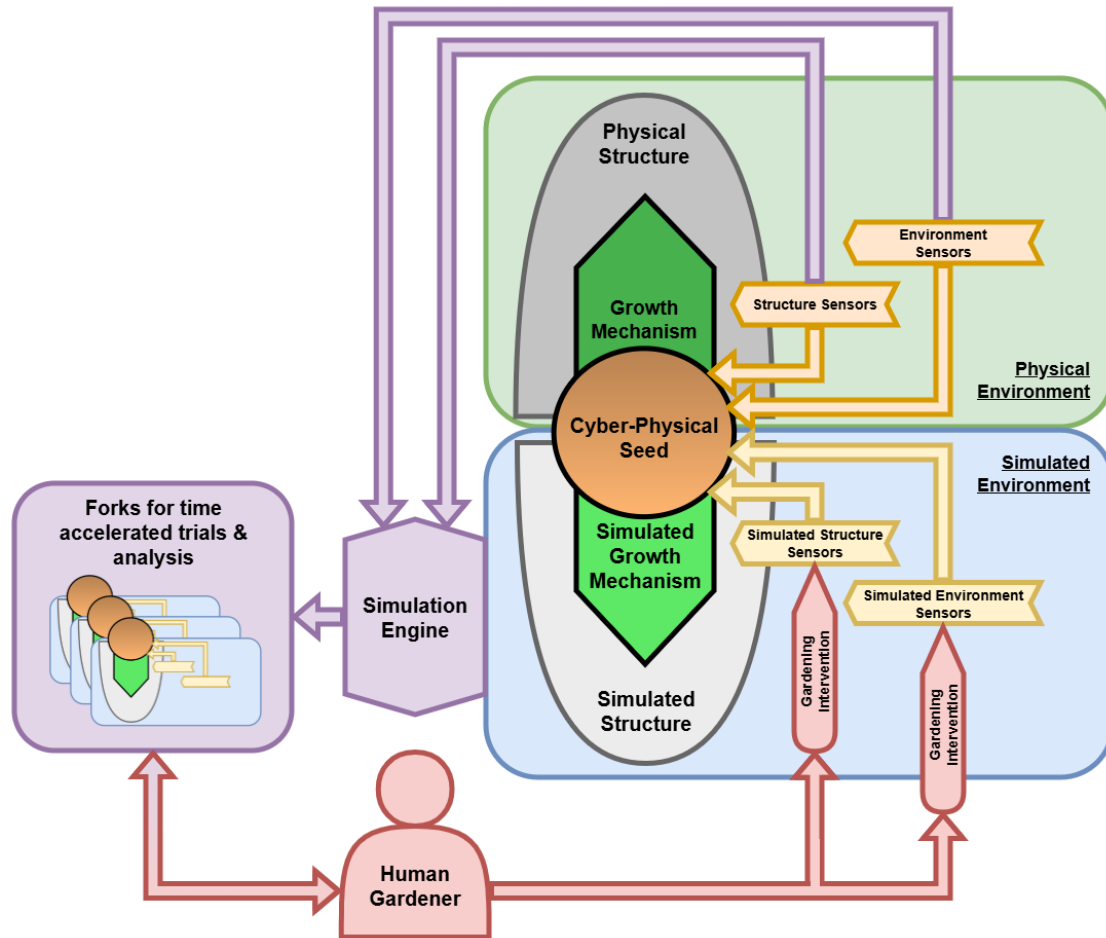


Figure 5: An illustration of the digital-twin based gardening concept for the monitoring and control of the growth of Zoetic Structures.

Returning back one last time to the roadway example. The physical Seed for the road is planted in the environment, and at the same time its digital-twin is planted in an initial virtual counterpart of that environment. As the two halves of the Seed grow together, data from the physical road is fed back to the digital one, updating it with information about the environment and its growth patterns. At any point, the gardener can take a fork of the virtual roadway and test out alterations, running it forward in time to determine the most likely development of the physical system. They can experiment with interventions on a model that can be constantly updated make its predictions as accurate as possible. And lastly, we can take an extra step and close the loop by making the final interventions in

the virtual world. If the gardener wants roadway to follow an additional path, the model of the environment held within the digital-twin can be manipulated to place a virtual trellis. This would then be fed back to the the physical system, thus causing it to start growing along a route that only exists digitally. The same concept could be applied to manipulate the growth in any desired fashion: from the placement of illusory impassable terrain to halt growth, to stimulating the development of specific features of the structure by by externally injecting signals to trigger their development.

4 Mechanisms of the Arcology Seed

As alluded to in the previous section, the starting point for a Zoetic Arcology would be its Seed, a cyber-physical artifact that contains within the genome of the Arcology, as well as the necessary mechanisms to read and implement this genome to start the growth process. Though exactly what these mechanisms are depends on the specifics of the approach, there are three things that are universal.

The Seed will require computational capacity; more specifically the ability to store, read and execute its genome. This could take the form of an inbuilt conventional computer, a hardware realisation of a neural or gene regulatory network, an application specific in-materio system, or something else, it does not matter. All that is necessary is the ability to translate between the genetic code and the control signals for the Seed's other mechanisms, modulated by incoming data.

The Seed will require hardware to allow it to sense the environment. At minimum the Seed should be able to assess the topology and material properties of the immediate environment, as well as monitor its internal state with a high degree of accuracy. This internal sensory requirement is important as it allows the Seed an awareness of the tools and resources it has at its disposal. While this could be satisfied by a simple list, having a sensory mechanism provides an awareness of any damage or malfunctions; and means

that as the structure grows, an awareness of newly acquired capabilities can be seamlessly. The Seed must possess is the ability to fabricate the first components of the structure. The role that the mechanisms of the Seed play in growth after this point is a properly of specific designs, but in all cases the Seed must be what produces the foundation. Furthermore, unlike the growth mechanisms within the rest of the structure, the fabrication mechanisms of the Seed do not need to be self-assembled. Unless we wish our structure to be able to reproduce itself, the Seed can be fabricated externally using conventional techniques. While this extends to the other components of the Seed, it is particularly useful in the case of the fabrication machinery as it allows the Seed to be used as a means to create parts or materials that either can't be produced by the growth mechanism or that we do not want the growth mechanism to be able to produce. This both allows for a broader range of possible growth mechanisms outside the Seed (as they do not need to be as complex), and allows the Seed to function as an important safety tool: shut down the Seed, and the system will stop growing.

4.1 What to Provide and What to Grow

When discussing the creation of artificial living systems, there is often a desire for said systems to come forth *ex nihilo*: to seek a hypothetical environment with a specific set of initial conditions and properties such that all the experimenter needs to do is press go, and in a few million time steps, a complex living entity has emerged. While the scientific merit of these kinds of ALife experiments is clear, when we wish to employ ALife principles in an engineering context it is obviously impractical. In the context of the Seed for the Zoetic Archology, this means that it is important to ask what tools and resources it would be best to allow the Seed to start with, rather than intending that the first parts of the growth process be the acquisition or creation of said tools and resources.

Let us say that the first major task the Seed must perform is to determine the location within

its environment of a source of water. It is therefore logical to suggest that among the Seed's the sensory mechanisms should be tools such as some form of directional hygrometer to deduce a likely direction to seek the water in. Designing a Seed with the intention that it would grow any sensors it needed from scratch when its first task necessitates specific information would be impractical. Armed with this information, two scenarios exist: in one, the Seed has been equipped with a mechanism for harvesting the water, so all that is needed is to deploy it; in the other, this mechanism must first be grown, analogously to a plant's tap root. Unlike the question of the sensory apparatus, both options have pros and cons. While a pre-built mechanism allows the acquisition of the needed water quickly and efficiently, it will have limits on its capabilities as a consequence of the decisions made during its design: it may only be able to operate in a finite range from the Seed, or might be rendered inoperable if the water contains over certain amounts of particulate matter. Overcoming these limitations is the strength of the grown option, but it suffers from the facts that it will take time to grow the collection system, and that any raw materials needed to feed that growth will either need to come from the Seed (which again is limited by what the designers thought to provide), or will need to be harvested from the environment, something that actually just cycles the question back again. How will the material to grow the pipe needed to gather the water be collected: a pre-built mechanism or a grown-for-purpose one?

There is no single answer to this question. Much like the juvenile forms of various organism of the natural world, different Seeds should be equipped with different mechanisms depending on their expected use case and environment; and what constitutes the difference between efficient and excessive will likely be subject to no small amount of debate. The key point is that expect a Seed to be little more than a computer, a general purpose fabricator and some initial feed stock is a perspective that will be impractical for the foreseeable future.

5 Archology Seed Genome

Much as in the biological systems from which inspiration is being drawn, the genome of the Seed must encode the information needed to inform all aspects of the structure's growth. That is not to say that this information will be explicitly encoded, something that is both impractical and unnecessary, but more that the design process must be informed by the fact that, even taking into account the oversight of the gardener, the genome is what will ultimately be dictating the structure's form and function. This in turn means that it is very difficult to tackle the creation of the genome without considering almost every other factor at play.

To begin, there is the question of how abstract the genome should be. This is both a question of direct vs indirect encoding (Stanley & Miikkulainen, 2003), but also of how nuanced the genome's perspective of the world needs to be. Consider a simple example: a genome that describes metal polygons. The obvious direct encoding version of this genome might be a tag denoting the specific shape (tetrahedron, cube, octahedron etc), followed by a number specifying the length of all sides. It should be obvious that this method heavily limits the genome to being only able to describe a finite list of regular polygons. However, an equally direct encoding would be a 3D matrix listing on an atom by atom basis the content of a volume of space. Both directly encode the polyhedron, but one is highly simplistic and thus limited, while the other has a phase space so large as to be basically useless.

It is this sort of conflict that has driven the popularity of indirect encoding methods, which also have the intrigue of being more biological. Indirect encoding schemes, however, require a methodology that translates the abstract genome into morphology of interest, and it is here that the previously noted point about the number of factors that need to be considered rears its head. Leaving to one side the dynamic aspects of a Zoetic structure and returning to the metal polygon example, let a hypothetical indirectly encoded genome

be a array of numbers that can be used as the parameters for an equation that plots shapes in 3D space. This obviously gives a generous parameter space while keeping the genome size quite small. However, we want these polygons to be something physical. The 3D plot is fed into a piece of CAD software that in turn produces instructions for some form of CNC machine, which then manufactures the polygon described by the array. The transcription mechanism is now no longer just the equation, but also incorporates the models of the CAD package, the algorithms that produce the CNC instructions, and the software and hardware properties of the CNC machine itself. Thus, any iterations on the genome must take into account these new aspects: can the polygon physically exist (i.e. does it contain geometry that isn't actually possible); what are the size constraints of the instruction file for the CNC machine; can the tool head of the CNC machine physically perform a particular maneuver that would be needed to machine a shape? Furthermore, what are the material properties of the metal the polygon is to be machined from? It might be possible to produce a particular shape, but have it fall apart as soon as it was removed from the machine because the material isn't strong enough to support a part of its geometry. Going beyond this simple example of metal polygons and the complexity of the transcription explodes, especially if the entity being encoded is in anyway dynamic or built of multiple components that must be fabricated and assembled together.

Considering even the most early stages of growth of a Zoetic structure, the design of the genome must take into account the various properties of the mechanisms of the Seed, as well as those of its initial feed-stock and the environment in which it is growing. As the structure grows, these factors will be joined by the properties of the structure itself and their interactions with the environment, as well as the interactions between the structure and its inhabitants. Regardless of the specifics of the design process, the first instinct we might have is to reach for the toolkit of simulation. If a model can be developed that encapsulates all the necessary information about the various factors affecting the growth process, then the various iterations of the genome can be tested using that model. High

performance computation can then allow for parallelisation of that testing process, both in order to test multiple possible genomes simultaneously, but also to allow for parameter sweeps to test variations of factors like environmental conditions. However, it is impractical to construct a model for testing that matches exactly the properties of the real world. There must be some degree of abstraction. This abstraction leads to one of the most prevalent problems with any simulation based approach to the creation of physical artifacts: the reality gap (Zagal et al., 2004). Any difference between the behaviour of a system in simulation and a counterpart in the real world is a manifestation of this, and it becomes very problematic if any form of automation is applied to the iteration of the simulated system, as it can lead to the development of unrealisable solutions. These can run the gamut from theoretically sound but impractical, such as the 20 meter thick lenses yielded by an evolutionary algorithm employed by Gagné et al. (2008); to the physically impossible, such as the physics engine exploiting soft robots explored in Cheney et al. (2014) (anecdotes taken from Lehman et al. (2020)).

Various approaches have been explored to address the issue of the reality gap, ranging from trying to improve the verisimilitude of simulators with things like noise injection (Jakobi et al., 2005); methods for assessing the limits of different models and how transferable to the real world designs they yield are (Mouret & Chatzilygeroudis, 2017); to the incorporation of explicit "manufacturability" tests into the design iteration process (Buchanan et al., 2020). While elements of these approaches may well have utility in this use case, there is another methodology, the groundwork of which has already been laid earlier in this section: that of employing simulation in close concert with real world counterparts. Obviously the parameters and model of any simulation that represents something real are informed by real world experiments, and an iterative process can be adopted of simulating, fabricating, testing and feeding back. What is meant here is instead an approach where simulated and physical versions of a system are evolved together, and with automated feedback between the two: the speed of the simulated system allowing for

a greater search space; and the verisimilitude of the physical system improving the real world applicability of the final product (Zagal et al., 2004) (Hale et al., 2019). Exploiting this principle to its fullest potential requires that the physical artifacts are monitored as closely as possible, that the data gathered can be fed into the simulated version, and that the physical and simulated versions can be produced from the same genome. It should be obvious at this point that these goals can be met thanks to the digital-twinning elements already present in the Zoetic structure's design. In essence, by starting the digital-twinning process before the design of the genome, it can already pay dividends by allowing the structure to be designed in this hybrid fashion.

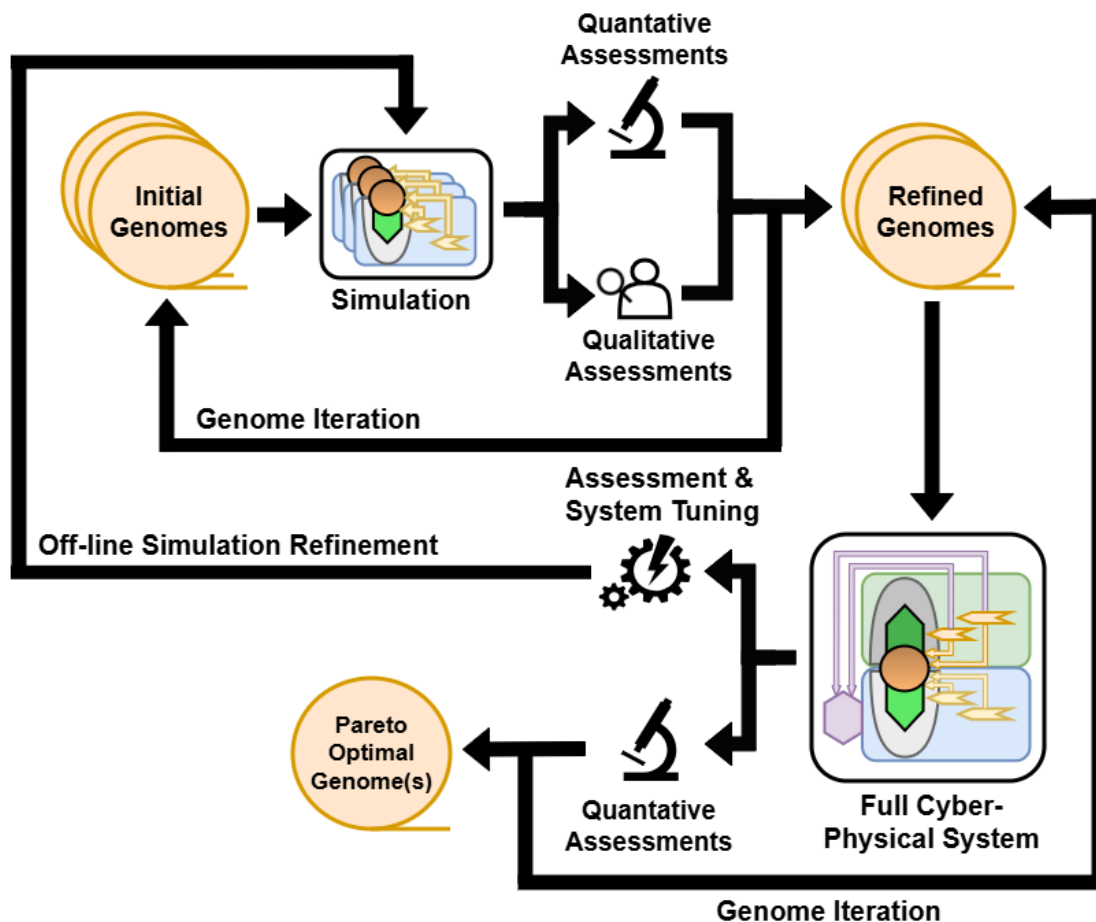


Figure 6: An illustration of the proposed hybrid approach for the creation of the genomes for Zoetic Structures

Figure 6 illustrates a method of implementing this hybrid approach. In it, pure simulation is used to provide data to perform an initial "rough sift" of the starting set of genomes. Those that pass that preliminary assessment are then implemented in the full digitally twinned cyber-physical system, which provides data for a more comprehensive assessment. Note also that, in addition to the refinement of the pure simulation similar to the refinement of the digital-twin, data from the full implementation is used to refine the metrics used in the preliminary assessment step. If features of poor, or high, quality solutions can be associated with factors measured at that earlier stage, then the performance of the whole design process can be improved.

5.1 Genome Evolution

With a methodology to attack the issue of the complexity of designing the Seed genome, the question of exactly how to carry out this design process can be addressed. Given the aforementioned complexity, it is expected that said design process would be automated, at least predominantly. We can divide the automation options available to us into three broad categories: domain specific algorithms, where an in-depth understanding of the process of transforming the genome into the final artifact is used to develop tools that allow a design to be translated into a genome that encodes it; artificial intelligence, where a neural network is developed that can be used to generate genomes that will produce specified designs (Friel et al., 2024); and search algorithms, such as evolutionary algorithms (Vikhar, 2016), novelty search (Lehman & Stanley, 2008) or quality-diversity algorithms (Cully & Demiris, 2018), where an algorithm navigates the phase space of possible genomes in order to locate one that encodes an end product that meets certain metrics.

The current state of the art when it comes to exploring artificial systems that exhibit growth is firmly covered by the final category. Quality-diversity algorithms and novelty search methods in particular have found great use in the ALife sphere as a means to explore

the diversity of the properties of living systems such as Lenia (Faldor & Cully, 2024). The reason for the appeal of such search methods is their broad applicability. They can be used to explore or design any system for which a metric can be described and minimal knowledge is needed about the behaviour of said systems. It is therefore logical to assert that such methods are what should be employed here. While novelty search or a quality-diversity algorithm will almost certainly provide utility in understanding the scope of what the Zoetic Structure system is capable of in the first instance, the bulk of the genome design process is likely to rest on fitness driven evolutionary methods, for the simple reason that there are requirements for what the final product of the system will be. The structure must be mechanically sound and physically possible to realise; it must be able to act as a dwelling place for a number of humans and meet various of their needs; it must be able to support its own existence for an extended period time; and so on. There are also aesthetic rather than technical considerations, especially given the principles of arcology design noted previously: the structure should blend with the surrounding environment, and it should be pleasing to reside in, as very few people want to live in substrate rectangles.

Capturing these many requirements and translating them into quantitative metrics that can serve as fitness scores is a non-trivial task, to say nothing of the need to also devise means of measuring and calculating the values of those metrics. How would one automatically measure and quantify aesthetic sympathy with the surrounding environment? Because of this, we suggest that it would be useful to use a staggered approach, where rather than trying to evolve solutions that fill all the requirements simultaneously. This has partly been alluded to in figure 6, with the idea of the preliminary vs full assessment of the possible solutions, but it can be taken further. Say we start with an initial population and assess them solely based on structural engineering metrics. This will yield a Pareto optimal set of individuals that can then be used to initialise the starting population for the next evolutionary process where, say, habitability metrics are the order of the day. This method partitions the search space, reducing the number of solutions that each step has to assess

without throwing out the important qualities that the assessed by the metrics in previous passes. Furthermore, if done correctly it would confer two additional benefits: on one end of the process, it might be possible to assess one or more of the sets of metrics solely using the simulated system, speeding up the process significantly; while on the other end, when it comes to the more subjective metrics, because they do not need to be assessed in parallel with their more mechanical\quantitative counterparts, human-in-loop methods such as Interactive Evolutionary Design (Takagi, 2001) could be used without sacrificing efficiency.

5.2 System Input or Fitness Metric

It is worth a quick aside to raise a question that should be considered when developing the fitness metrics for a system such as the one under discussion: what of those factors that could be treated as either fitness metrics or inputs to the system itself? To use an example, let us reduce the scale of the system to one that grows a single house. How many people will reside in said house? A single occupant, a small family, a larger group sharing and so on are all viable options. Is this figure then plugged into the evolutionary process as a fitness metric, with structures in the population assessed based on how well they house that many people; or instead does the system take occupancy as part of some specification, with the evolutionary process including a fitness metric based on how well the whole specification is met?

As with many such questions under consideration in this work, there are pros and cons to each. In the former case, if factors like occupancy are used as fitness metrics, this reduces the size of the potential search space, speeding up the process. On the other hand, this limits the flexibility of a given genome, requiring specific genomes be evolved for each variation of the metric. The latter case is then just the opposite: the individual genome is more flexible, but the evolutionary process takes longer as a wide variety of

possible specifications must be tested, thus increasing the search space. In the end, where different parameters fall on either side of this dichotomy is not a question with a simple answer. Instead, careful consideration should be made of each factor at play, and decisions made with an eye on the resources available to the specific research effort.

5.3 Single or Multiple Seeds?

For simplicity, the illustrations in figures 5 and 6 show only a single Seed from which every element of the structure is grown. However this is not the only option, and it may be more desirable that a structure would be grown from multiple Seeds operating in symbiosis. In the example of a building, one Seed may grow the underlying superstructure; another the electrical wiring and lighting; while a third forms the water system etc. Like increased degrees of indirect encoding, the use of multiple Seeds has pros and cons. While individual Seeds can be less complex and there is no need for them to be implemented in the same fashion, their interactions and the signaling system needed to facilitate them is non-trivial, particularly when considering the interplay between the relative positions of each Seed. That being said, there is a phenomena in nature that might serve as a source of inspiration to attack these concerns: Ecological Succession. Defined as the change in the types and ratios of species in a community overtime, it can be most readily illustrated through the example of Forest succession, shown in figure 7.

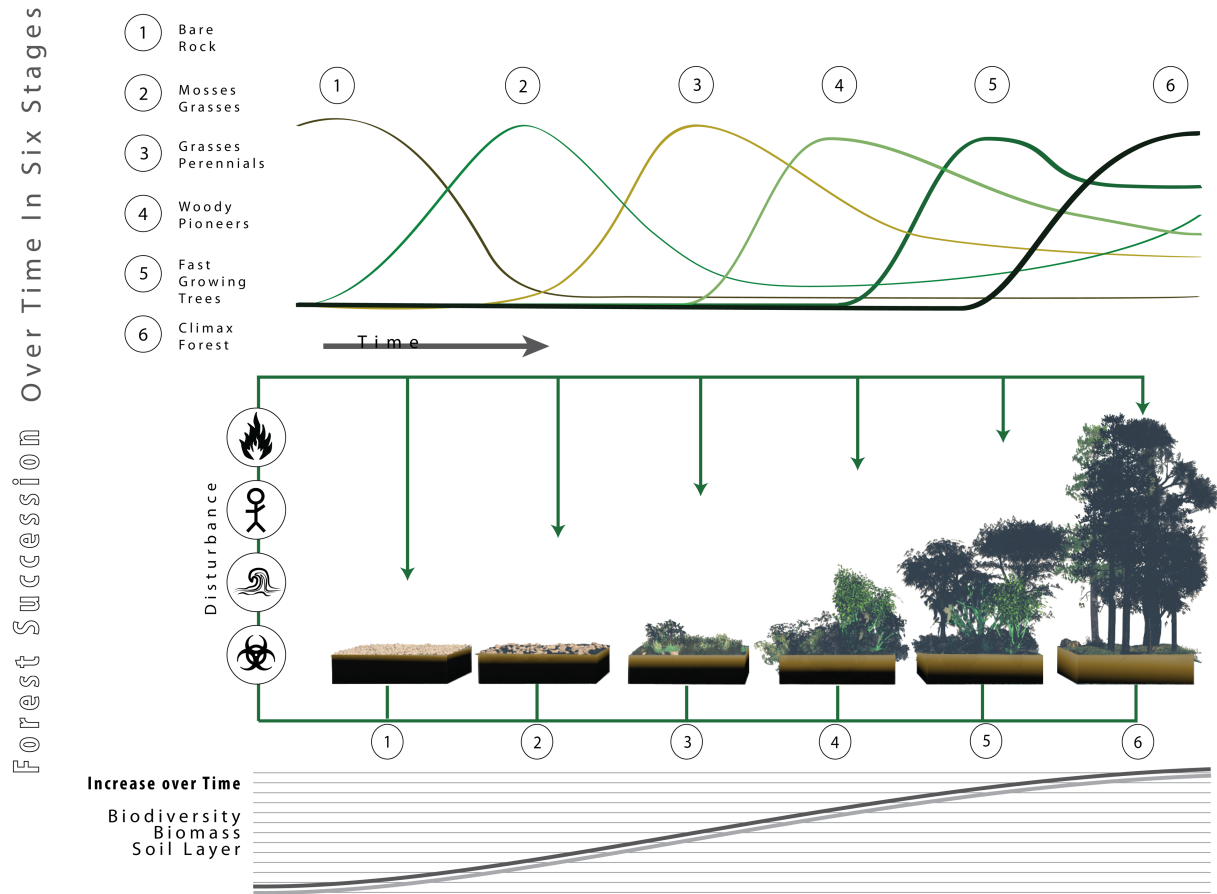


Figure 7: An illustration of the phenomenon of Forest Succession, whereby successive groups of plant species drive the alteration of a rocky landscape to a well developed mature forest (Wikimedia Commons, 2011)

Different plant species are optimised for and tolerant of different environmental conditions; conditions that are often created by other plant species. In the first instance, so called pioneer species like mosses and lichens will colonise areas of bare rock, gradually breaking it down into sparse soil. This can support low growing grasses and shrubs, which enrich the soil until it can support woody plants, leading to the establishment of fast growing and eventually slower growing tree species; which in turn will create ideal conditions for species like shade lovers, epiphytes (plants that grow on other plants) and, after death, fungi. Furthermore, as successive waves of species rise, those optimised for previous conditions reduce in number, either dying back almost completely, such as with the pioneer species, or to a level commensurate with the carrying capacity of the new environmental

470 conditions (McEvoy, 2004) (Budowski, 1965).

471 Applying this same principle to the case of Zoetic structures allows for a multi-Seed ap-
472 proach that leverages a kind of passive communication via the state of the environment.
473 For example, the first species of Seed acts as a resource concentrator, harvesting mate-
474 rials from the environment, stockpiling and transforming them. When the measured levels
475 of specific materials exceed a certain threshold, the next species "germinates", consum-
476 ing a portion of the materials to grow the foundations; the appearance of which cause the
477 "germination" of the superstructure Seed, and so on. The environmental triggers could
478 also be more artificial, such as a species of mesh networking Seeds which grow when they
479 pick up another wireless signal, spreading connectivity outwards in a wave.

6 Endogenous and Exogenous Growth

The natural world builds a lot of structures, and for the purposes of this section we can divide them into two loose groups. First are those structures whose growth is Endogenous, that is to say the structures grow themselves such as the trunks of trees. The other group is those structures that exhibit Exogenous growth, such as the hives of colonial bees.

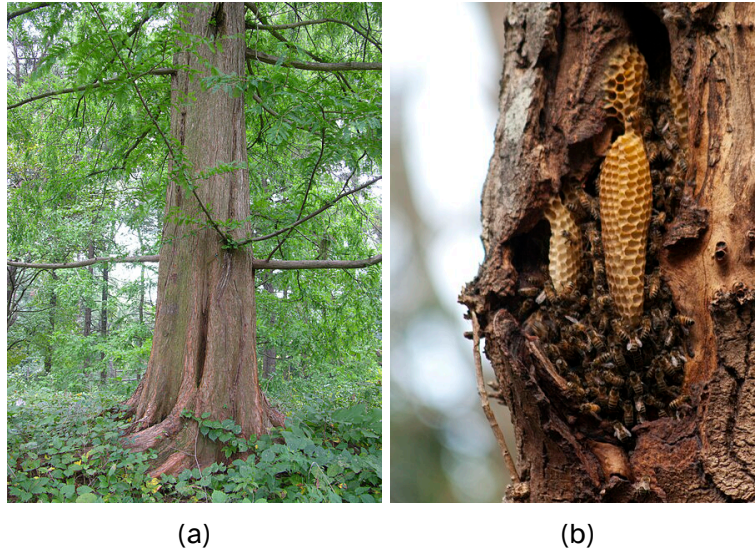


Figure 8: a) a Dawn Redwood (*Metasequoia glyptostroboides*) tree (Wikimedia Commons, 2006); b) a beehive within the hollow of a tree (Wikimedia Commons, 2010a)

While discussions can be had about whether this division is meaningful from a systems perspective, for the purposes of this work these two categories are important because they frame a crucial question: should the fabric of our Zoetic Structure be assembled or self-generating? Are we growing a plant, or building a hive?

6.1 Endogenous Growth

For a structure to be able to display Endogenous growth, the material that that it is composed of must be capable of self-replication. The theory of self-replicating artificial systems goes back to John von Neumann's work and the idea of the Universal Constructor architecture (Von Neumann, 1966); something that was later integrated into the nascent field

of nanotechnology with Eric Drexler's conception of nanorobotic "assemblers" (Drexler, 1986). While advancements have been made in simulated environments (Baugh & McMullin, 2012) (Clark et al., 2017), physically embodied artificial self-replicators continue to be confined to small scale fluid environments (Kriegman et al., 2021), while the state of the art for molecular scale fabrication remains largely limited to the theoretical (Tarasov et al., 2012). This has caused a shift in thinking away from crafting such mechanisms from scratch, and instead seeking to leverage the abundant molecular machinery provided by biology. Stepney (2014) evokes synthetic biology as the tool for realising living structures, and it best embodied by the work associated with Prof. Rachel Armstrong. Armstrong (2023) provides a philosophical overview of this body of work, along with a survey of efforts in the two areas currently under development: building materials and building services.

The later of these two will be expanded upon later, as the subject of biologically derived materials is more directly relevant to the question of growing the Arcology. Armstrong (2023) highlights a number of promising bio-derived materials, with three of interest here being Mycelium Biocomposites, Biolith, Bioconcrete. The later of these two exploit Biomineralization, the same phenomena that gives rise to Coral Reefs. Coral Polyps, relatives of the jellyfish, are sessile marine animals that, while soft bodied themselves, extrude Calcium Carbonate skeletons which provide support for the colonial organism that is an individual coral; while multiple corals in concert lead to the creation of the underlying structure of a whole coral reef (Sorokin, 2013). Biolith is a concrete alternative, where the conventional chemical process of cementing materials through the conversion of Calcium Oxide (derived from Calcium Carbonate at significant energy and carbon emission costs) into various silicate containing minerals is replaced by using *S. Pasteurii* bacteria, which produce Calcium Carbonate while consuming Carbon Dioxide, resulting in a material comparable to sandstone (Jølcck & Perez, 2022). Bioconcrete meanwhile is instead a means of extending the useful lifetime of conventional concrete by impregnating it with *B. Pseudofirmus* and *B. Cohnii*, two species of bacteria that respond to the ingress of water by forming various

carbonate minerals. This has the effect of allowing the Bioconcrete to heal from cracks, thus preventing the need for its premature replacement (Sharma et al., 2017).

Mycelium Biocomposites, as the name might suggest, employ fungi as their biological component, exploiting the mechanical properties of fungal mycelium to bind together a plant derived bulk material, often sourced from agricultural waste like rice husks (Fairus et al., 2022). While quite mechanically weak, these materials are also very light, giving them a superior strength-to-weight ratio to concrete, encouraging their use in the creation of arch or dome structures. The two primary methods employed when working with Mycelium Biocomposites are either: the use of a monolithic formwork, much like for pored concrete, which is then filled with fungi inoculated bulk material that is allowed to grow to fill the formwork; or the creation of blocks of Biocomposite which can then be joined together either conventionally or by encouraging the fungi within the blocks to grow together (a process called myco-welding) (Dessi-Olive, 2022).

That said, despite the clear potential and utility of these, and other, living materials, there is a crucial shortfall in the current state-of-the-art when it comes to their application in this context: shaping. In most cases Biomineralised materials and Mycelium Biocomposites are shaped into the desired structural form through the use of a mold or scaffold, left to their own devices they will not create useful structural forms. The Seed itself could be treated as the scaffold, an augmented version of the methodology discussed in Adamatzky et al. (2021), but this would either place limits on the final size and shape of the structure (if the Seed's morphology was fixed), or create a chicken and egg problem if it was required to grow.

However, a solution to this issue is suggested by picking up on a thread in Goidea et al. (2020), which details some promising work in the use of 3D printing to produce Biocomposite structures without the need for formworks. Specifically, they demonstrate this idea by producing Mycelium Biocomposite duplicates of the fungus combs found inside the

mounts of some termite species. Examples of Exogenous growth.

6.2 Exogenous Growth

In biology Exogenous growth, that is to say those structures built by living organisms but which are not themselves composed of living tissue, is strongly associated with the Eusocial insects: the Hymenoptera (ants, bees and wasps) and Blattodea (termites). The nest\hive\mound building of these various species is a well known phenomena and, other than the dam building of beavers, is perhaps the most often cited example of the "engineering" prowess of the animal kingdom. The important thing is that Exogenous growth is not a learned process: it emerges from ingrained aspects of the organism's physiology. A queen bee does not need to be taught how to direct her new swarm to create honeycomb and build a hive; instead the workers, all individually following a set of simple rules, construct the comb by instinct, with it having even been demonstrated that a large enough swarm can do so without a queen (Škarka et al., 1990). Given these facts, it is no surprise that there is a rich body of work that seeks to derive models of eusocial insect construction (Bonabeau, 1997), and to then apply such models to the challenge of creating mechanisms that can be employed for real tasks (Parker et al., 2003) (Werfel et al., 2014). The work by Werfel et al is of particular interest to this effort, as they were able to demonstrate a "compiler" tool that translated a human specified design into a set of simple local rules that their trio of robots followed to build simple structures from provided blocks.

It is by combining this kind of phenomena with the growing and regenerating biomaterials discussed previously that the optimal form for the mechanics of the Zoetic Arcology emerges. Insect swarm inspired construction agent can be realised in the physical world via robotics, allowing them to be wed them to the digital-twin based gardening methodology. They can lay down the superstructure by extruding biological inoculated bulk material, which an then in turn grow and solidify the final form, guided by pruning and training by

the workers and all under the direction of the Seed: acting as queen of this mechanical hive.

6.2.1 Worker Integration

In the simple model of Exogenous growth, workers do two things: gather materials and build. However, there is no reason why that should be the end of it, and biology can once more be a source of inspiration. There are obvious tasks, such as the completion of a portion of the structure triggering behavioral change, switching workers from construction to acting as cleaning and repair agents (Cushman, 2022), but there are two specific examples within the world of eusocial insects that point to another interesting possibility.

The honeypot Ant, or Honey Ant, is the common term for several species of ant across Africa, Australia and North America that share a fascinating evolutionary quirk: a sub-caste of workers that act as living food stores. So adapted to this role are they that Repletes, as this cast are called, remain largely stationary, with some species exhibiting a behaviour where their Repletes will hang from the ceiling of one of their nest chambers, forming a strange living larder (Conway, 1986). There is also the genus *Cephalotes*, sometimes also nicknamed "door-head ants". These ants make their homes within cavities inside trees, and in order to protect them from invaders the soldier caste has developed a behaviour called Phragmosis: the use of their bodies to block the nest entrance. In many species of *Cephalotes* however, such as *C. varians* and *C. persimilis*, this behaviour has led to the evolution of a rather odd adaptation. The soldier cast of these species have developed large, flat, disk-like heads which they employ as doors (Powell, 2008).

These examples represent organisms becoming an integral part of the structure their colony has created. By the same token, construction agents in the Zoetic Arcology could become similarly directly integrated into the structure. For example, what if periodically a construction agent deliberately embeds itself into the walls of the structure as its fellows build

it around them? There, its sensory apparatus provides that portion of the structure with perception, both for self-regulatory mechanisms and the digital-twinning system; while its networking capabilities allow it to function as a router for communications between the structure, construction agents, the Seed, and even potentially human occupants. If the construction agents possess a power supply such as photovoltaics, they could permanently anchor themselves to the outside of the structure to provide it with power; while those agents carrying bioreactors, either for power generation or the production of the biological materials needed for construction, could continue to monitor and replenish the vital microbial components of the Arcology.

6.2.2 Biological Building Services

The concept of Biological building services as articulated in Armstrong (2023) concerns the application of microbial or algal bioreactors to tasks like energy harvesting (Sedighi et al., 2023), waste treatment (Armstrong et al., 2017) etc. Both these examples have demonstrated additional potential: with a pilot Microalgae building facade project in Hamburg utilizing algal bioreactors to supply heat and electrical energy, while also sequestering carbon dioxide through the algae's growth and improving the building's thermal performance (ARUP, 2022); while Hogle et al. (2023) explores the use of bioreactors hosting engineered strains of bacteria integrated into building to not only clean waste water, but produce electrical energy and useful materials like detergents or fertilizers.

There are other ways in which existing or engineered biological life could be leveraged to perform useful functions within a Zoetic Arcology. The use of plants for the treatment of waste water is a mature technology (Cooper & Green, 1995) and brings the added benefit of providing a wetland environment that can be colonised by animal and plant species in line with the goals of Reconciliation Ecology. Kumar et al. (2023) and others have demonstrated the application of algae as a method of air filtration, yet another dividend of their use. Engineered microbes as tools for detecting compounds is also a growing area of

research (Su et al., 2011). These microbial biosensors are a very interesting concept in this application, as among the methods of "reading" the data from them are various optical approaches, based on mechanisms such as the production of fluorescent or colorful proteins, or fully fledged bioluminescence. In the case of the Zoetic Arcology, colonies of engineered microbes could be embedded within the structure as directly human readable instruments.

7 Construction Materials

It is finally time to address more fully something that has been raised a few times throughout this work: the subject of construction materials. We cannot create something from nothing, so just as conventional building calls for bricks and mortar and living organisms call for food and water, our Zoetic structure has its own pseudo-metabolic needs that must be met. While in our initial experiments we will most likely be meeting these needs artificially, that is to say hooking the structure up to curated external supplies of material, the ultimate goal must be a system able to meet all its needs by extracting material from its surrounding environment. Whether providing a Zoetic structure with an internet connection and allowing it to order concrete deliveries represents cheating or a novel survival in the Anthropocene is left up to the reader to determine.

With this in-situ resource utilisation in mind, we must confront the following fact: modern conventional construction materials are almost universally a) found in specific geographic locations b) not co-located and c) demand non-trivial amounts of processing to convert from raw to usable form. Concrete, the most widely used construction material in the world (Crow, 2008), is composed of water, aggregate and a cement, typically Portland. Water is of course relatively abundant, as are aggregates suitable for use in concrete. Portland cement on the other hand is created primarily from limestone, and more specifically limestone which is over 97% Calcium Carbonate ($CaCO_3$). Taking the United Kingdom as an example,

limestone that meets this requirement is located almost entirely within the Peak District (in the Midlands) and the Lake District (in the North West of England) (British Geological Survey, 2006b). Once extracted, the limestone must be crushed to a fine powder, mixed with similarly powdered clay (usually geologically adjacent to suitable limestone) and fired in a kiln to produce cement clinker (British Geological Survey, 2014). This clinker is then ground and blended with Calcium Sulphate ($CaSO_4$, also called Gypsum and extracted at a few sites in Leicestershire, 50km from the Peak District and 200km from the Lakes District (British Geological Survey, 2006a)) to produce the final product. This issue only grows when further materials are considered: Silica Sand of a grade suitable for the production of glass is found overwhelmingly in Cheshire (50km from the former and 160km from the latter (British Geological Survey, 2020)), and requires high temperatures and admixtures like borax (Sodium Borate $Na_2H_{20}B_4O_{17}$, which comes primarily from America (Klein & Hurlbut, 1993)) needed to complete that sand's transformation. There are no conventionally viable deposits of Copper left in the UK (British Geological Survey, 1998); plastics require oil; ceramics sophisticated kilns; and so on and so forth for the many materials needed to finalise a modern structure.

All this can be distilled down into the assertion that our Zoetic structure must take an alternative approach. It must rely on different materials, extracted and processed in novel ways. Furthermore, this new approach must be baked in from the very beginning as it will inform every other part of our thinking: the mechanisms of the Seed and capabilities of the construction agents must be able to extract and work these materials; the morphology of the structure itself depends on their mechanical properties; and our ability to implement aspects like electrical infrastructure relies on getting materials with specific properties. We have already discussed the use of a number of bio-materials previously; and to augment those possibilities we will look at two other options should be able to provide for our needs: the use of locally abundant materials and the exploitation of waste.

7.1 Abundant Materials

What do we mean by "locally abundant materials"? It is admittedly a broad, perhaps overly vague term, so let us provide a definition for this context. A material can be considered locally abundant if, within a given area where a structure is to be created, said material 1) is present in an amount such that the growth of the structure will not cause it to be depleted; 2) comprises a significant proportion of the total material present; and 3) can be introduced into the growth processes without excessive extraction and refinement needs. Given that the question of whether a material conforms to this definition or not is highly location specific, let us instead consider a few materials that it is reasonable to assume there exists a site where one or more of them would be abundant.

Soil, in all its various permutations, accounts for 12.5% of the Earth's surface (Moore et al., 2020). With said surface area being $510.1 \times 10^6 \text{ Km}^2$, applying a very conservative soil depth of 0.1m yields $6.37 \times 10^6 \text{ m}^3$ of material. Putting said material to use for construction is something with prehistoric precedent and covers a few different techniques including the use of earth and fiber mixtures such as Adobe or Cob; the transformation of earth into building blocks such as Mud Bricks; or the method that might be of most interest here: Rammed Earth Construction. As its name might suggest, Rammed Earth Construction is a conceptually simple technology. First, a formwork (mold) similar to the kind used for poured concrete is created in the desired shape; a layer of soil, either unadulterated or mixed with a binding agent, is loaded into this form; before manual or mechanical force is used to compact the soil layer. Once completely full of compacted material, the formwork is removed revealing the completed section (Maniatidis & Walker, 2003). While the typical binder used to improve the structural properties of the soil is cement, recent work has demonstrated promising results using bio-polymers such as Casein (found in milk) and Ovalbumin (found in egg white); with the later demonstrating a high degree of water resistance and a compressive strength greater than clay brick (Ouedraogo et al., 2019).

Furthermore, various methods of automating the process of creating rammed earth structures have been developed, including techniques that involve moving formworks (Gomaa et al., 2023). Taking these two lines of research together, it is very possible to envision a set of construction agents doing as the mound building insects do: ingesting earth, blending it with a binding agent and extruding it out to form elaborate structures.

The Sahara covers an area of $9,000,000 \text{ Km}^2$, and while only 20% of that area consists of dune bearing sand seas (Pastore et al., 2021); a conservative average sand depth of 20m leaves a generous budget of $3.6 \times 10^{13} \text{ m}^3$ of material. While glass might be the first use that sand conjures to mind, it is much simpler and more useful to transform it instead into a structural material: Sandstone. In nature, the compression of sand under its own weight leads to the lower layers of the column fusing together to form rock, often with the aid of the introduction of materials like quartz that act as a bonding agent (Crook et al., 2024). Given the apparent simplicity of this process, it is unsurprising that it has been artificially reproduced, typically in the interests of investigating the effect of different material compositions or formation conditions on the properties of the resulting sandstone. Al-Homadhi (2002) describes probably the most obvious methodology, with mixture of sand and sodium silicate being compacted using a press to produce articles similar to geological core samples; a process that can easily be re-imagined as a method for producing sandstone "bricks". A more unusual approach is outlined in Konstantinou et al. (2021), where a more structurally weak form of soft sandstone is created by impregnating the sand with a calcium carbonate producing bacterium (*Sporosarcina Pasteurii*), with a view to the use of this technique in a geotechnical engineering context for applications like slope stabilisation or erosion mitigation. It could be in this fashion that it would be applied to our context, i.e. the introduction of a bacterial workforce to create a foundation for a structure. Tangential to the interests of the geological world, sand based 3D printing has quietly developed, primarily driven by a need for the foundry industry to produce complex sand moulds for the casting of metal components. While the state of the art is to use

Furan or Phenolic resins (Upadhyay et al., 2017), there is no reason to suggest that it would not be possible to employ one of the geological options mentioned above in their place.

The volumes of materials listed above pale into insignificance next to the $1.3 \times 10^{18} m^3$ of water that make up the world's oceans (National Oceanic and Atmospheric Administration, 2024). While this might not seem like the most useful building material, 3.3% of this volume comes from 5×10^{16} tonnes of dissolved salts rich in Sodium, Magnesium, Calcium, Chlorine, Sulphur and Bromine; at least some of which can be extracted at a scale to make them commercially viable (Loganathan et al., 2017). The natural world, however, has been exploiting this chemical treasure trove for far longer than us, with some of the largest animal made structures on the planet standing as a testament to this fact: coral reefs. Coral Polyps, relatives of the jellyfish, are sessile marine animals that gain their energy by snatching small food particles out of the water as they drift by, augmented by sugars provided to them by symbiotic single celled organisms called Zooxanthellae. While the Polyps themselves are soft bodied, over time they will extrude Calcium Carbonate, forming structures which provide support for the colonial organism that is an individual coral; while multiple corals in concert lead to the creation of the underlying structure of a whole coral reef (Sorokin, 2013). Inspired by this mechanism, Hilbert (1979) describes a means of replicating it, allowing the dissolved minerals in sea water to be used for the creation of arbitrarily shaped structures. Hilbert's method calls for suspending a metal mesh with the desired geometry in sea water (acting as a cathode), and then running an electrical current (Terlouw (2012) suggests a voltage of 1-24V at a current of 3A per meter squared of cathode) between it and a similarly suspended anode. The resulting "Seacrete" (or "Biorock") structure has mechanical and thermal properties comparable to concrete (Johra et al., 2021), while also being self-repairing so long as the electrical current is maintained and increasing in strength over time as the mineral composition shifts from faster to slower accreting compounds (Terlouw, 2012). While currently finding use primarily as a tool for coral reef restoration, Hilbert (1979) articulates the possibility of applying the technique to

the building of habitable structures at sea; also briefly describing an alternative approach to the pre-built cathode in the form of an extrusion mechanism that lays down a cathode wire as it "rides" along the previously grown "Seacrete" behind it.

7.2 Exploiting Waste Material

Naturally occurring materials are not the only thing that can be found in useful concentrations for our purposes. Since time immemorial human societies have been generating waste products, a growing percentage of which do not degrade over time and instead accumulate at their disposal. While statistics for specific disposal sites are not readily available, Burnley et al. (2007) provides a breakdown of the municipal solid waste (MSW) stream of Wales for the year 2006, from which we might make some inferences. Of the 1.6×10^6 tonnes of MSW there were, among other things: 344,900 tonnes were paper and cardboard; 119,200 tonnes of various plastics; 95,100 tonnes of glass; and 32,700 tonnes of Waste Electrical and Electronic Equipment (WEEE). Together with figures from 2012-13 that indicate 40% of MSW in Wales went to landfill (Statistics for Wales, 2023) (640,000 tonnes from the above 1.6×10^6 tonnes); and the count of 20 operational landfills currently remaining in the country as of 2018 (Natural Resources Wales, 2020) (32,000 tonnes per year per landfill). Assuming an active lifetime of 10 years, we could make the following estimation of the contents of a given inactive landfill: 68,000 tonnes of paper and cardboard; 23,000 tonnes of plastics; 19,000 tonnes of glass; and 6,000 tonnes of WEEE.

7.2.1 Paper, Cardboard, Plastics and Glass

Construction is not the first application that comes to mind when considering uses for paper and cardboard, but its prevalence in household and industrial waste has pushed for investigation into all possible ways to put the discarded material to good use. In what will become something of a theme, the survey (Oriyomi et al., 2015) indicates that most of the research in this direction has looked at using waste paper as an admixture for conven-

tional concrete; either simply to bulk out the concrete or to try and produce light-weight concretes, sometimes referred to a "Papercrete". Resin or cement bonded recycled paper can be used to produce a version of Particleboard, which is typically made from sawdust, though it is more susceptible to the adverse effects of water. Composites of recycles paper and plastics, generally called Hybrid Composites, could also be a worthy avenue of investigation, especially as their reported thermal properties make them a good fit for insulation applications (Eires et al., 2006).

Awoyera and Adesina (2020) presents a survey of the current options being explored for the use of plastic waste as a material for construction purposes. Again, many of these focus on the use of mechanically recycled (i.e. shredded) plastics in place of aggregates in conventional concrete and asphalt, with the addition of a use as a base for the laying of roadways. The former of these could integrate well with some of the soil and sand based methodologies described previously. Akinwumi et al. (2019) investigated the use of shredded plastic as stabiliser for compressed earth bricks, showing significant improvements to their compressive strength; while Kumi-Larbi et al. (2018) discusses the creation of Low Density PolyEthylene (LDPE) bonded sand blocks. This possibility is particularly attractive as a) the process Kumi-Larbi et al describe is quite simple (the LDPE is melted, mixed with sifted sand and molded); and b) LDPE is both widely used (primarily as a packaging material) and infrequently recycled (Di et al., 2021).

Glass has a well established recycling process, as it is possible to take crushed waste glass (known as Cullet) and use it as part of the mixture of raw materials for new glass, which has the added benefit of reducing the energy consumed by the heating process (Dyer, 2014). In construction applications, once more, it can be directly used as an aggregate substitute in concrete etc; though more interesting is its possible use as a Pozzolanic Material (Mohajerani et al., 2017). Pozzolans are a category of Silicon or Aluminum based materials that react with Calcium Hydroxide in the presence of water to form Calcium Silicate and

Calcium Aluminate compounds like those created by hardening Cement (Jackson, 1998). While this has not yet been able to be shown to be able to fully replace Cement in Concrete, it does indicate it might be possible to formulate a waste glass/Calcium Hydroxide based construction material. Furthermore, Calcium Hydroxide can be obtained by roasting and then hydrating Calcium Carbonate, suggesting a possible methodology where by a "Seacrete" reef might be used to "farm" the necessary material.

7.2.2 Waste Electrical and Electronic Equipment

Waste Electrical and Electronic Equipment (WEEE) is a broad grouping of waste material, but it can be better understood by following the six categories set out by European Parliament (2012): temperature exchange equipment (refrigerators, air conditioners etc.); screens, monitors and equipment containing a screen larger than 100cm^2 (televisions, computer monitors, laptops etc.); lamps (all kinds); large equipment, i.e. any external dimension more than 50cm (washing machines, ovens etc.); small equipment, i.e. all external dimensions less than 50cm (toasters, microwaves, kettles etc.); and small information technology and telecommunications equipment (mobile phones, PCs etc.). Note the absence from this definition of items such as industrial equipment or electric vehicles, as they have their own disposal legislation for reasons beyond the scope of this discussion. These categories yield a material breakdown (by weight) as follows: 44.7% Ferrous Metals; 18.3% Plastics; 12.2% Glass; 7.5% Non-ferrous Metals; 2.2% Printed Circuit Boards (PCBs); and 15.1% other (ADEME, 2013).

Given the amount of WEEE produced, the value of some of the materials within it (remember that the 7.5% non-ferrous metals fraction contains the Rare Earth Metals), and the hazards that can be posed by improper disposal (WEEE can contain materials such as Arsenic, Cadmium, Mercury, Lead, Phosphorous-containing compounds, Asbestos, glass fiber etc. (UK Health and Safety Executive, 2022)) it is unsurprising that the recycling of WEEE is an area of significant research that has yielded a number of approaches of varying degrees

of efficacy (table 1 of Innocenzi et al. (2017) provides a summary). While it is possible to envision a small scale implementation of one or more of these various approaches, most likely as components of the Seed due to the material demands, for our purposes there is another possibility worth exploring.

Outside of the confines of the industrial waste recycling paradigm, there exists a growing ecosystem of hobbyists, engineers, artists, repair technicians, and activists who breath new life into discarded electronics through activities that Lu and Lopes (2024) group together under the term "Unmaking". The parts of this Unmaking ecosystem that are of interest here are "Tear Down" (the dismantling of waste electronics to acquire their components) and "Upcycling" (the use of these harvested components to create new objects) as, to frame the idea very directly, there is little point in implementing an energy intensive industry derived material recycling pipeline to harvest scrap copper and extrude it as new electrical wiring, when there is plenty of scrap electrical wiring that can be repurposed. It is also worth noting that it need not be necessary for components extracted to be fully functional for use to be extracted from them. A growing category of electronic waste is the batteries of electric vehicles, which are typically no longer suitable for automotive once they have lost 10-20% of their capacity, however they are more than sufficient for applications such as grid energy storage(Kotak et al., 2021). It may even be possible to go further, as it has been suggested that computer processors too damaged to function conventionally could be repurposed for reservoir computing applications (M. Trefzer, personal communication, July 2022).

On a different tack, the application of biotechnology to metal extraction might seem initially to be an unusual idea, but it is one that has attracted growing interest. A survey by Lee and Pandey (2012) focuses on the recovery of metals from waste sources produced directly by conventional metallurgical processes (smelter flu gases, slag, mine tailings etc), and reported that a variety of methods employing bacteria or fungi were able to recover

iron, copper, aluminum, zinc and nickel with good levels of efficiency. Işıldar et al. (2019) reports similar levels of success with a feedstock of WEEE, noting multiple approaches with both high levels of efficiency and technology readiness levels of 4 or higher. This sort of approach could work well in concert with the upcycling methodology discussed previously, with material too damaged to be directly reused being fed into the bioreactors to yield fresh raw metals.

7.3 An Aside on Energy Generation

One thing that has not been explicitly addressed thus far is the question of providing the energy, predominately in the form of electricity, that will allow the various mechanisms of a Zoetic structure to function. The metabolism of biological systems generally exploit light (photosynthesis) or chemical energy (either from the environment such as deep ocean dwelling chemotrophs, or the energy within other organisms for saprotrophs, herbivores, carnivores etc). As both photovoltaic and solar thermal electricity generation are mature technologies they are a logical starting point, especially given that as a renewable and emission-less source they are easier to align with the Arcology principle of ecological harmonisation; though current photovoltaic systems do call for materials and manufacturing techniques that could limit their ability to be produced in-situ. Solar energy might also be exploited through so called "Artificial Leaves", an ongoing area of study that seeks to produce devices able to convert atmospheric carbon dioxide and water into hydrocarbon fuels using sunlight at ambient temperatures and pressures (Olmos & Kargul, 2015). Furthermore, current efforts in this area have a strong focus on the use of abundant materials, something beneficial to this application (Ampelli et al., 2023). Another path to the indirect use of solar energy through chemical energy would be to exploit the ability of many species of Microalgae to produce Hydrogen from water under certain conditions (Jiao et al., 2024). Another highly flexible option would be a thermal generator, either employing the thermo-

electric effect or a mechanical heat engine and dynamo. Such a system would be able to leverage heat sources like solar concentrators or geothermal heat, but it would also open up some more unusual possibilities. Due to a combination of bacteria driven breakdown and chemical and biochemical reactions between the materials within, landfill sites can reach internal temperatures of between 60° and 90° C, with some industrial waste disposal sites reaching in excess of 100° C (Yeşiller et al., 2015)(Jafari et al., 2017). Hanson et al. (2022), using a very conservative temperature of 40° C, calculated that such a landfill contains 238 Megajoules of heat energy per cubic meter of waste, while also noting the side effect that the temperature reduction increased the landfill's production of combustible gases (predominately methane), which can also be burned to produce power. Bacteria driven gas production is also the mechanism behind biogas digesters, also called Anaerobic Digesters, which have become a mature technology over the past few decades due to their efficacy at producing energy from organic waste including animal and human excreta (Deng et al., 2020). A Zoetic structure could therefore possess a "stomach", digesting down waste material from the environment, its inhabitants, and itself; with the produced biogas then being transported to the "generator organs" to produce electrical and thermal energy.

8 Conclusion

While the vision presented in this work may seem to be quite speculative, we would argue that far more of the parts of this undertaking exist than we might expect. From design philosophies perfect for joining with the ideas of Artificial Life, to evolutionary developmental pipelines that suggest a way to realise those philosophies; from inspirations from the natural world about how we might make best use of the tools we have at hand, to construction paradigms that tell us the same raw materials that nature uses can be ours to use too. It is also important to note of course that this work is by no means exhaustive.

Though the author has at least attempted to have something to say on as many areas of this idea as possible, volumes could be written attempting to assess the full state of the different arts called upon. Furthermore, while the author has endeavored to present a mix of ideas, this work also represents only one perspective on the problem. There are likely as many different paths forward in this challenge as there are people who take an interest in it.

That being said, reaching there from here is still a significant undertaking, and one that is best tackled incrementally. As such, we shall conclude this work with a roadmap, outlining the route by which the Zoetic Arcology may be realised.

8.1 Roadmap

It should first be noted that, while purely simulation based experiments will likely be part of the initial stages of work, it is imperative that a true cyber-physical artifact be the focus. As such, we would suggest that a worthwhile preliminary goal would be to build a constructor system consisting of: at least one mobile construction robot; its digital counterpart; and the system for interconnecting them. As this development is occurring, experiments to assess different construction materials can be carried out, which in turn inform the design of components of the constructor; though at this stage said material would be externally prepared and supplied rather than being processed by the constructor. Once in a suitably functional state, evolutionary techniques can be brought to bear, iterating controllers for the constructor as assessing them based on the properties of the structures they bring forth. At this stage, these structures will be of a lab bench scale and comprised of a single material, but important information can still be gathered on different controller architectures, genetic encodings, evolutionary methods, fitness metrics etc.

At this stage it would also be logical to begin experiments with gardening interventions, which are likely to take two forms. The first is the practical work that would be necessary to

get the system to work: investigating the optimal balance of complexity and efficiency to allow for time accelerated forecasting using the digital-twin; assessing different feedback methodologies and getting them to satisfactorily impact the behaviour of the constructor etc. The second line of investigation would be from the perspective of Human Computer Interaction (HCI) & creative practice, looking into both the gardener interface, how the gardener interacts with the constructor; as well as what kinds of structures could be realised with a human element guiding the constructor.

With this foundation, the complexity of the cyber-physical constructor and the desired structure can be incrementally increased. A meaningful stage three might be to introduce a second constructor (of broadly the same design), whose goal is to enhance the base structure produced by the first. This could start with the second constructor operating only once the first one's work is complete (something that would allow for the two constructors to actually be the same system just with hardware swaps and software switch over); with the work iterating to a stage where both constructors are present in the environment from the start, taking cues from each others actions and working together to produce the more complex structure. This second stage would also be the logical place to begin imparting of active properties to the structure, both through the materials being used and the embedding of the construction agents into the structure.

Stage three could go in a few different directions, but would most likely consist of a combination of investigations into: enabling the constructors to harvest and process their own construction materials; expanding the complexity of the structure by introducing additional elements such as scale electrical infrastructure; as well as starting to introduce human centric or ecological concerns into the structure metrics. This is also the stage where moving beyond the laboratory bench to larger scale experiments is likely to become necessary, and would ideally end with the production of the first demonstration of the idea of a Zoetic Arcology: a structure on a human scale that possesses meaningful living properties and

958 that was created in full by the constructors.

959 It is the final transition that would represent the greatest undertaking however, as at this
960 stage it would be necessary to take the constructors and package them up within a Seed.
961 This is where the hard questions about how much of the constructor the Seed should build
962 vs what should come "pre-packaged" must be answered. The evolutionary aspect of the
963 work would grow in complexity as this stage, as we would no longer be evolving controllers
964 for the constructor; the controller and mechanisms of the Seed which builds the constructor
965 which builds the structure that the fitness metrics assess. It is also the point where systems
966 must be designed to replace the nurturing environment of the laboratory, as the constructor
967 that the Seed brings forth should be able to meet as many of its needs as possible by itself;
968 no helpful technicians to recharge batteries or refill material reservoirs can be allowed.
969 The scale would also expand again and represent a transition from controlled conditions
970 to the real world, something else that adds to the difficulty of this stage. However, if this
971 last set of hurdles is successfully navigated, the end result will be a true Zoetic Arcology
972 Seed: a device able to bring forth a large scale human habitation from locally sourced raw
973 materials, that is able to maintain itself while harmonizing with the natural environment,
974 and that does so with only light guidance from its gardeners.

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