Chapter 1

Towards an Agile Biodigital Architecture: Supporting a Dynamic Evolutionary and Developmental View of Architecture

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Additional information is available at the end of the chapter

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Abstract

Architecture and biology are fields of high complexity. Generative design approaches provide access to continuously increasing complexity in design. Some of these methods are based on biological principles but usually do not communicate the conceptual base necessary to appropriately reflect the input from biology into architecture. To address this, we propose a model for analysis and design of architecture based on a multistaged integrated design process that extends the common morphological process in digital morphogenesis with a typology-based ontological model. Biomimetics, an emerging field to strategically search for information transfer from biology to technological application, will assist in delivering a frame of reference and methodology for establishing valid analogies between the different realms as well as integration of the biological concept into a larger framework of analogy to biological processes. As the biomimetic translation of process and systems information promises more radical innovation, this chapter focuses on the dynamic perspectives provided by biological development and evolution to model the complexity of architecture. The proposed process was used to inform five parallel workshops to explore dynamic biological concepts in design. The potential of the process to investigate biomimetic processes in architecture is then discussed, and future work is outlined.

Keywords: biomimetics, evolutionary design, morphogenesis, morphogenetic prototyping, agile design principles

1. Introduction

This chapter identifies a multistaged integrated design process for the analysis and design of architecture, which extends the common morphological process with a typology-based ontological model. Architecture involves the design, control and manipulation of a multitude of complex systems to result in a successful building. Therefore, there is a continuous exploration of the transfer of models from external disciplines into architecture to support modelling and ultimately the control of this complexity. For instance, generative design allows the exploration of various design solutions based on the definition of design-specific representations and generative rules and behaviours, which allow to iteratively generate designs in a bottom-up process.

Some of these methods are based on biological principles [1–3], and as evolutionary theories in biology are radically revised [4, 5], the terminology in this context needs to be revisited to include novel biological concepts. Biomimetics provides methods to communicate the conceptual base from biology into design and has promoted novel approaches to architectural design [6]. Morphological processes targeting formfinding have previously been explored in digital morphogenesis [7–9]. Additionally, McGinley [10] proposed a framework to support the integration of concepts of biological development into architectural design while also exploring the concept of agile design. Therefore, we propose and discuss a method to support designers to integrate biological concepts of development and evolution in their work.

At the same time, it is important to caution that biology is a broad discipline, which is built from a multitude of perspectives. Tinbergen defined these as the four questions of biology. The questions divide biology into dynamic and static views which are then each subdivided into how and why questions. The dynamic views consider why the organism evolved and how it developed into the biological artefact, whereas the static view interrogates a biological artefact at a single point in time. In biomimetics, this is paralleled by material, structural, process or systems translations from nature into technology.

Computer science links biological concepts to architectural application, serving as a bridge between biology and design. Therefore, this chapter applies adapted agile design methods from computer science in architecture, proposing a strategy for translation of biological observation on a system level to computational design systems in architecture using evolutionary and genetic principles. To create a test bed for this conceptual approach, a design workshop event 'Agile X4' focusing on the South Australian housing typologies was organised to create a proof of concept case study.

2. Evolution in design

Evolution and natural selection are characteristic signs of life, which result in a continuous improvement of the biosphere by providing resilience, adaptation and development. These properties are also desired in architectural design processes. Therefore, a review of the evolutionary concepts in the realm of architecture seems to be a promising approach to build on the recent developments in evolutionary architecture that adopt a computer science method for the generative development of design solutions. Evolution as a strategy has been applied to a technical context as an optimization strategy since Ingo Rechenberg pioneered evolutionary computation in the 1970s [11, 12]. Rechenberg's Evolutionary Strategy (ES) served to solve complex optimization questions in science that could not yet be tackled by theoretical approaches. This methodology is aimed at improving technical optimization and is thus embedded in the context of technology.

The architectural discourse about the use of evolutionary computation in generative design processes is based on the introduction of Genetic Algorithms, developed by Holland [13] and Genetic Programming, introduced by Koza [14] to the scripting practice for architectural design tools. The pioneering work of Frazer [1] provides a strong knowledge base for architectural designers to come to explore the possible applications of evolutionary computation. In the section on genetic language, Frazer points out that multiple levels of representations determine the genetic hierarchy required to develop a living organism. Additionally, there is potential for the use of language characteristic elements, vocabulary and syntax, as described by Contreras and Chomsky [15–17]. In this context, the complexity of representation for architectural design is already tangible.

Recent developments in computer science that use grammatical evolution [18–20] extend the repertoire of generative design strategies with an evolutionary approach using a reduced representation even for complex design cases. These systems build on the rule-based approach in shape grammar [21], but encompass the potential to drive the unfolding of computational designs based on behavioural systems in bottom-up processes.

3. Biomimetics

Biomimetics, an emerging field to strategically search for information transfer from biology to technological application, assists in delivering a generic frame of reference and methodology for establishing valid analogies between different realms. Defined as an innovation methodology, the process of biomimetics involves basic research, abstraction of principles and translation of those principles into an application field. Biomimetics deals with materials, structures and systems, but typically extracts knowledge about functions, mechanism or concepts that are then applied by designers or interpreted by engineers. Moreover, the interdisciplinarity inherent in biomimetics holds the potential for radical, new innovations and sustainable products and technologies [22].

Biomimetics has been increasingly explored in the context of architecture, design and the arts in the last decade, and a biological paradigm seems to underlie current trends in design research [23]. Examples for biomimetic applications at the scale of materials and surfaces are self-cleaning or easy-to-clean coatings on glass and metals and also facade paint. Structures and constructions informed from biology, especially from plant structures, are explored in prototypical buildings like the ICD/ITKE pavilions and also include products like flectofin, a novel facade-shading system using a compliant mechanism inspired by the opening mechanism of the flower of the bird-of-paradise (*Strelitzia reginae*) [6]. Most recently, aliveness of architecture is discussed within the context of growth of material structures and agency. Growth principles from biology are increasingly explored in computation, generating a new morphological space that is transferred into material systems by additive production technologies like 3D printing. Metabolic activity as a base for all life is also explored in architectural design by creating matter and energy flows in prototype installations, in addition to the use of algae and bacterial as integral and active elements into wall, facade and soil systems [6, 24, 25].

Methodologies and tools for biomimetics are being developed primarily to facilitate the knowledge transfer for the technology side. Translation tools, databases such as AskNature [26] and methodologies such as BioTriz [27] have not been introduced on a large scale yet. A very concise description of the process of biomimetics can be found in the German VDI Standard [22] and in publications of the Biologically Inspired Design at the Georgia Tech Institute [12]. A new and intriguing way forward is the development of an ontology for biomimetics [28]. Ontologies deal with the definition of entities and their relations. Biological principles can be expressed in computational representations and ontologies to inform computational design processes.

The introduction of biomimetics in the field of evolutionary and agile design allows the integration of those concepts into a larger framework of design and analogy to biological processes. It provides a methodology for analogy building, abstraction and information transfer and promotes process and systems translation into technology. As a frame concept, biomimetics requires a reinterpretation of mimicking evolutionary processes in design. Apart from material representations of architecture referring to biological materials and structures, phylogenetic history and genetics of the role model refer to dynamic translations and distinctive design processes.

4. Agile design

Project management methods can be defined as either predictive or adaptive. Predictive models rely on the information of the project being fixed at the start of the project and that which is unknown being accurately predicted. Alternatively, adaptive methods support variability in the requirements and constraints of a project. Samset and Volden [29] propose a series of paradoxes of predictive project management. These can be summarised in that many important decisions about a design project need to be made at its start, when we know the least about the project. The strategic errors resulting from these myopic decisions are further frustrated by any misalignment of the selected tactical approach to realise the chosen strategy.

Alternatively, the founders of the agile movement defined a manifesto [30] with a set of principles for supporting a more adaptive approach to the development of software. The fourth principle, responding to change over following a plan, provides the underlying principle for agile design. Agile design approaches achieve this by working in cycles so that decision making can be more flexible (agile) and changes can be made later. Built environment projects are traditionally predictive, which can mean that changes can be difficult to implement. One major advantage of biomimetics is that it provides a broad body of potential solutions for a project but that implementation of each example requires the design model to adapt. Therefore, we propose that employing agile design principles in architecture could support

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further exploration of the design opportunity space which will better support the implementation of dynamic biomimetic concepts in architecture [31].

Furthermore, the model abstraction provided by the computational lens allows for a deeper investigation of the biological analogy of evolution and architecture and expands the knowledge transfer to have a direct impact on the process of architectural conceptualisation. In this way, computational design approaches such as evolutionary programming and agile design support adaption of design models of continuously increasing complexity in design.

5. Multistage design process

To support biomimetic concepts such as evolutionary design in architecture, this chapter employs agile design concepts to facilitate the exploration of the opportunity space of architectural design. This is proposed here in an abstract model for the analysis and design of architecture based on a multistage design process. This process uses the following stages of (1) identifying the features of the design; (2) extracting pseudo-genes from the features; (3) establishing the phenotype (what the evolved and developed typology would look like) and finally (4) altering the genes and repeating the previous steps. In this way, the process extends the common morphological process in digital morphogenesis with a typology-based ontological model.

5.1. Identify the features

In the first stage, the features of the typologies are identified as the input data for the system. These features could include distinct architectural elements, spatial entities and relationships that characterise the typologies. This process results in a feature matrix that can be translated into a computational system.

5.2. Define the genes

This phase identifies the 'genes' of the design, based on the feature matrix. In an analogy to reverse engineering, existing features lead back to the rules of creation. These rules could be thought of as design genes [10, 32].

5.3. Model the phenotype

The next stage is to generate virtual phenotypes based on the feature matrix and design genes. McGinley et al. [33] proposed that the architectural phenotype is based on environmental influences on the (architectural) genotype. For modelling the phenotype, there are several options:

- A model based on voxels – dividing the space up into boxes that could then be spatially allocated
- A model that we describe as a 'bag of beans', which involves a randomly distributed but static set of 'nuclei' that are grouped, shelled or hulled depending on the spatial position information

- A dynamic computational fluid dynamics model wherein the nuclei (cells or beans) can move and be moved by gradient forces inside the pseudo-organism.

5.4. Modify the phenotype

The virtual representation of the phenotype is evaluated in a selection process. Evaluation can take place against a chosen set of criteria in the digital realm, or can introduce modification by external influence in a virtual reality environment. A modified phenotype results from this phase. Feedback from this last phase can then connect back to the input data or abstracted gene stage. In order to trace the flow back to the initial data stage, a real world translation is required.

6. Case study (Agile X4: morphogenetic prototyping)

The Agile X4 event at the University of South Australia in Adelaide served as a test bed for the conceptual approach. The proposed workflow of the integrated design system requires the collaboration of multiple disciplines: architecture theory, data experts, biology, computational design, computer science and programming, virtual reality experts. The integration of multidisciplinary design teams generates the necessity for the establishment of communication protocols on both the level of human interaction and the level of systems interaction. The validity of the proposed model was investigated in the workshop event called 'Agile X4'. During the timeframe of 1 week, five parallel workshops were conducted with an international team of 29 researchers and students. Together, the five workshops covered the workflow described in the previous chapter, mapping the workshop activities to the integrated design process (**Table 1**).

The workshops started simultaneously and ran over 5 days, with an integrated conference and synthesis time to coordinate and connect the results. The activities, tools and methods of each phase are described here based on the workflow model of the multistage design process (**Figure 1**). The main flow of information was established, leading from research in architecture

Workshop	Description	Input	Define	Model	Modify
Carve	Prototype a tangible user interface (beyond pencil, keyboard and mouse) [34] for multistage process				✓
Design X	Define a VR experience for defining and altering the phenotypes			✓	✓
Evo Type	Provide an evolutionary perspective on the history of the South Australian House and identify its 'genes' and adaptations over time	✓	✓		✓
Reverse	View the typical Adelaide house as if it had developed biologically		✓		✓
BioMod	Develop the generative explicit geometry for the case study			✓	✓

Table 1. Mapping of the parallel workshops of Agile X4 to the integrated design stages.

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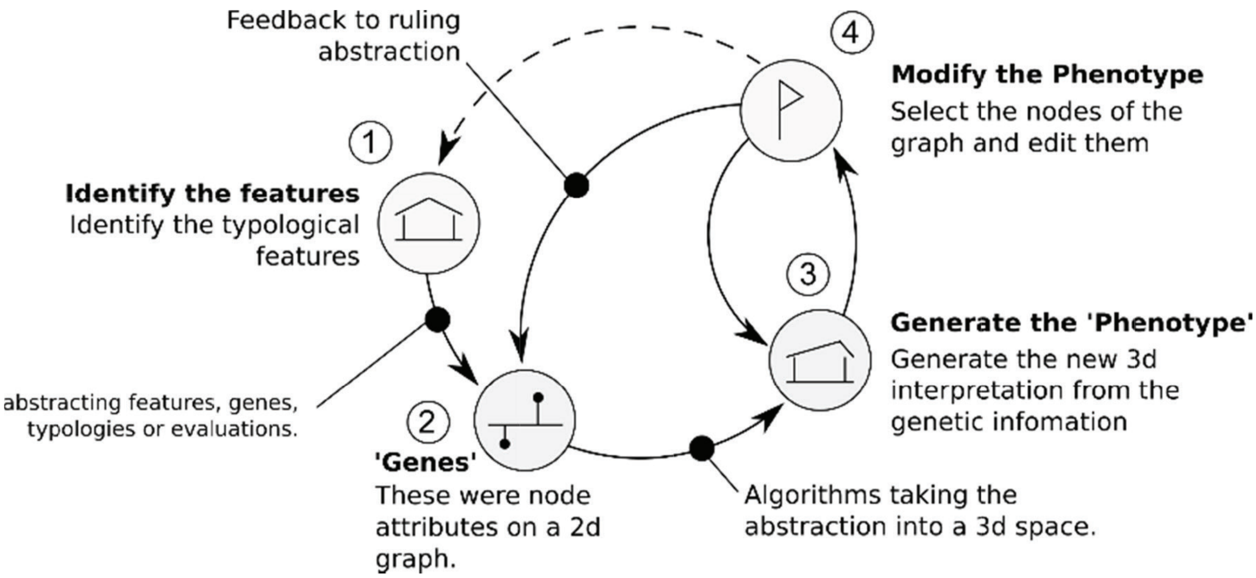

Figure 1. Stages of the agile biodigital design process.

history over typological interpretation, abstraction of spatial information into topology diagrams and ontologies, creating organismic analogies by differentiation into body plans, translation into an analogy to genetic information, generation of a new spatial interpretation based on environmental parameters and modification using interface tools in a virtual environment to finally feeding the modified information back into the cycle.

6.1. Identify the features

South Australian housing typologies were used as the base architectural input model. In collaboration with UniSA Architecture Museum, a literature research and archive research were carried out, and a set of building drawings selected and analysed. This enabled the identification and selection of specific features that were then encoded in a diagrammatic topological map and a feature matrix of the houses along with the basic data including, for example, date of construction.

6.2. Encode the genes

The next stage based on the feature matrix was to identify the 'genes' of the design. Spatial features of the South Australia houses were translated into connectivity diagrams (**Figure 2**). The Evo Type workshop provided an evolutionary perspective on the history of the South Australian House. It was then possible to model a developmental perspective for each typology based on a hierarchy derived from its connectivity diagram.

6.3. Generate the phenotype

The graphs (connectivity diagrams) generated in the gene encoding stage were sent from Grasshopper to control pheromone growth of a particle system in Maya that was rendered in real time as a series of boxes in Unity (**Figure 3**).

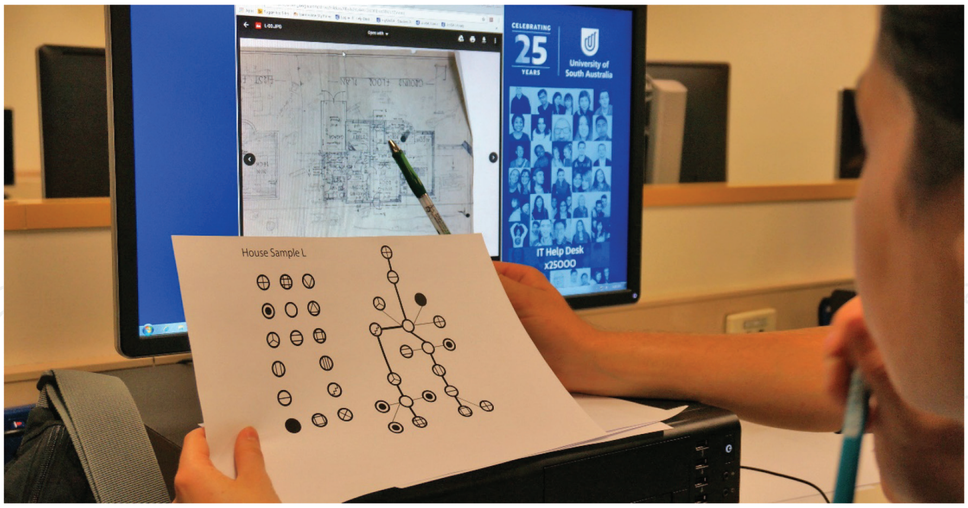

Figure 2. Adelaide house types with their connectivity graphs (photo credit, Petra Gruber).

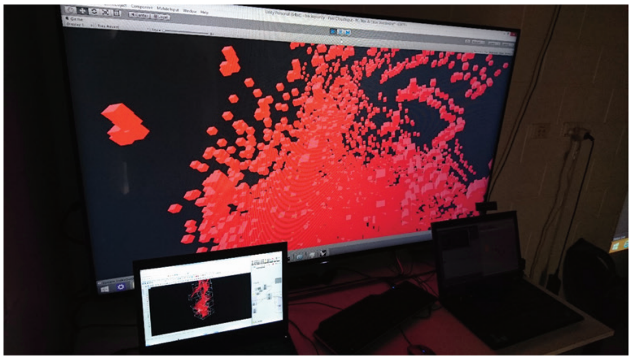

Figure 3. The generated phenotype based on the connectivity diagram interpreted in grasshopper and Maya into Unity.

Figure 4. Design X workshop tutor Daish Malani testing the gene adaptation prototype agile 'axe' (photo credit, Kelly Carpenter).

6.4. Modify the phenotype

In parallel, the carve workshop produced a tangible user interface prototype in the form of an axe. This enabled the user to select and modify specific nodes in the connectivity diagram in a virtual reality space, thereby altering the pseudo-body plan of the architectural typology (**Figure 4**).

7. Results and discussion

During the translation of knowledge from developmental biology to architectural design, we realised the immense potential to extend morphogenetic design methodologies. In response to the changing perspective on evolutionary and developmental processes in biology, the architectural interpretation of morphogenetic design was revisited. The extension of the evolutionary design model with a typological ontogeny was facilitated in an iterative design process. During the process, the knowledge about the problem was built in multiple groups, each responsible for a stage in the explored multistaged design model. After an advanced design state was achieved in one of the groups, the integration with neighbouring groups in the design model led to an increased level of integration. At this crucial moment, knowledge was successively transferred between interacting groups to provide an embedded understanding of the process. As a result, a rigorous argument was developed to communicate between groups. Evidence of the design process inside the distinct groups was used to transfer and communicate embodied knowledge between those groups. The research on a new multistage design process provided a validation of the comparison of genetics and architectural typology and an extension of the basic analogy of evolutionary architecture.

The agile process of the workshop allowed us to develop the communication model for the integrated design system on the fly. The communication protocol and initial workflow of the design system were developed, implemented and tested during the workshops. Limitations and challenges were found in the translation between the distinct phases. Building a shared computational representation during the workshop was the biggest challenge. The initial desire to translate implicit knowledge stored in traditional typologies to modern design approaches was not fully reached based on the time constraints. A prototypical software implementation for a design process that would be able to facilitate reaching this goal was investigated and tested. The outcome of the workshop was therefore a result of a rigorous investigation on the geometric translation and computational communication of the implicit knowledge inside the explored topology. As a result, an interactive methodology for a multistaged adaptive design system was successfully tested using an abstract geometrical representation. The selection mechanism in a virtual environment was crucial to the overall success. Here, the concept was the manipulation of the graph model based on the user input. As this was not tested in a closed-loop system before, the potential of the user guidance of the design process through gesture has yet to be explored. The main barrier to implementation during the workshop was the complexity of the data that should be mapped from the gesture to the computational model. Overall, the use of a persistent graph model for the testing of computational design systems proved to be a feasible approach to reduce the system complexity. It allowed to test the workflow in the brief period of the workshops.

8. Conclusion

This chapter proposes the development of a system to design active tools based on agile principles integrating biological models in a new multi-stage design process. The combination of an agile approach on the level of human interaction with the use of biomimetic principles on the systems level allowed us to establish efficient protocols and use the synergetic effects between computational design systems in architecture and systems design based on biomimetic principles. The multistage computational model was developed and tested in an initial design experiment of Agile X4.

The outcome of the workshop series was in many respects promising:

- The results of the feature matrix during the definition of the ontological input were successfully used to generate a dynamic representation of the explored typology of the South Australian House.
- The main advantage of the agile approach is the modularity of the system that is based on the specification of a communication protocol shared over all stages of the design process. It allowed the use of a variety of design tools that are available in the CAD software packages of Rhinoceros, Maya and Unity. A developmental model for generative design was used to develop a flexible graph model as communication protocol in the computational design system.
- Based on the developed design system, further investigations on geometrically refined representations promise to transfer additional knowledge from the traditional typology to state-of-the-art computational design processes capable of exploring large design spaces.

There is an enormous potential for form generation in reference to existing typologies using the developed multistage design system. Furthermore, a four-dimensional mapping of the genotypes to the phenotypes would encourage speculation about topological changes introduced by the aliveness of architecture.

9. Future work

The further development of the proposed multistage design process entails improvements on various levels. Firstly, the basic analogy between architectural design and evolutionary development should be revisited and recent findings in the life sciences integrated into the translation. Novel concepts such as niche construction theory and epigenetics have not been sufficiently discussed in the context of the built environment.

Secondly, for the distinct phases of the design process, further research would provide further understanding of the flexibility inherent in the design system. So, for the gene extraction, the number of features that are mapped between genotype and phenotype should be increased, and for the phenotype modelling, the mapping of building features in a particle system would drive the development of the phenotype through existing typologies. The implementation of a flexible graph model would allow the mapping of the defined genotype on a four-dimensional space-time model. Additional research should also be conducted on the behaviour of the system interaction of different typologies with each other (ecology simulation). The relation of typologies to environmental context is another interesting field of research that could be further investigated in a comparative study over different climatic and cultural zones.

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